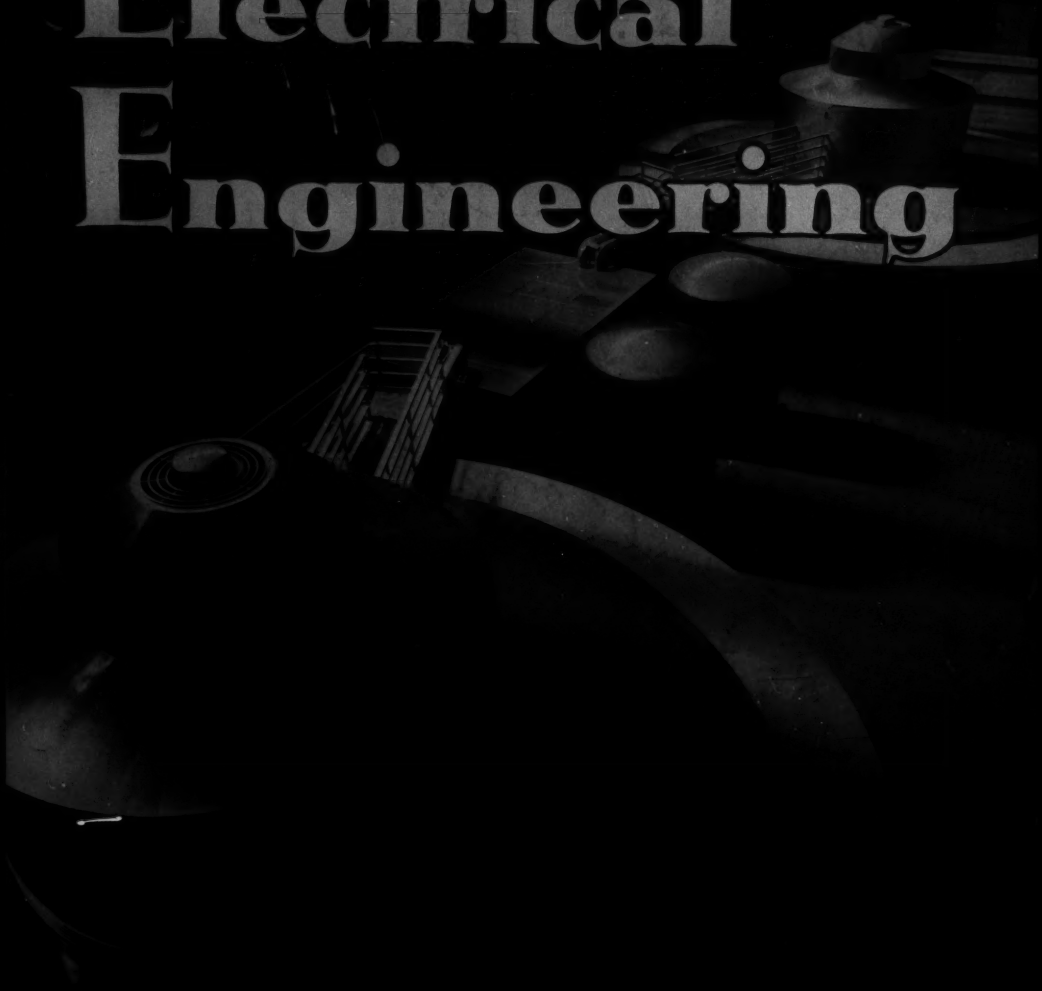
Electrical Engineering

February
1940



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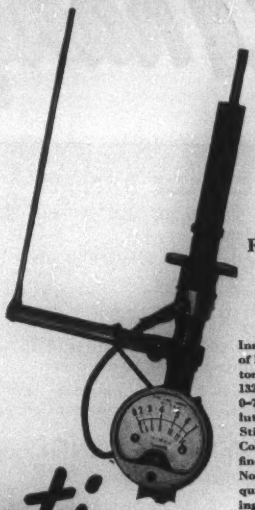

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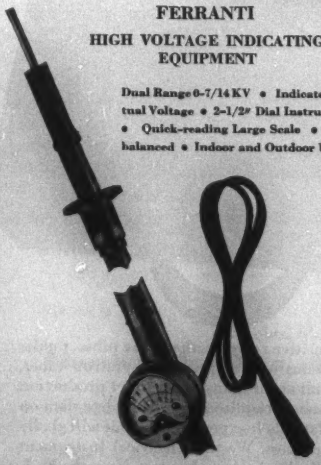

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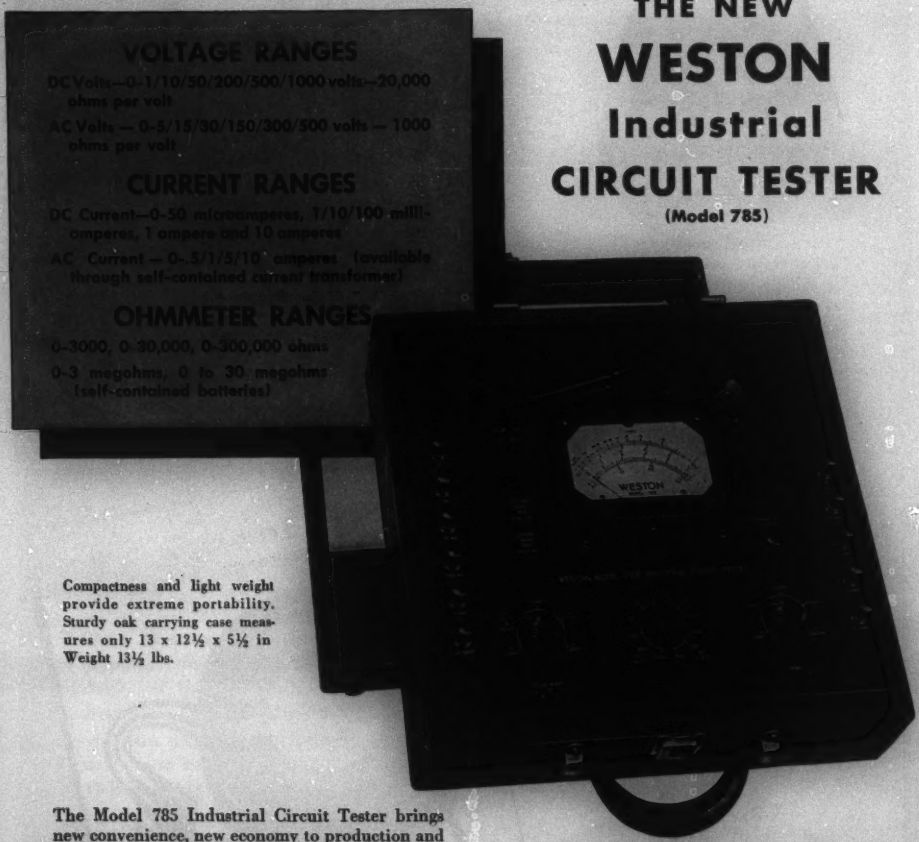
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Electrical Engineering

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for February 1940—

The Cover: The two 36,000-kw main generating units in the Pickwick Landing plant of the Tennessee Valley Authority. According to an article in this issue (pages 59–62) the electrochemical industry is the only one able to utilize the large amounts of power being made available at such Federal projects.

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¶ Correspondence is invited on all controversial matters.

High Lights • •

Electricity in Chemical Plants. Many chemical plants, which are among the largest industrial users of electric power, find electricity essential for obtaining the high temperatures required in their processes; in plants where the relatively low temperatures required may be obtained from steam, there are many opportunities for the production of inexpensive power for driving equipment, illumination, and other uses from combined steam and electric generating plants. Special precautions must be observed in selecting equipment because of the fire or corrosion hazards in most chemical plants (*pages 77–83*).

Steel Mills. The decline in production of heavy rolled steel products, such as rails and plates for railroads, structural shapes and plates for the building industry, and large welded and seamless pipe, during the past decade has been paralleled by a rise in production of light flat-rolled products for the automotive, container, and other industries. This shift in requirements, together with revolutionary developments in manufacturing equipment and processes, has resulted in the installation of many new strip mills and associated equipment (*pages 70–7*).

Nuclear Disintegration. Outstanding research accomplishment of 1939 in physics and chemistry is recognized to be the discovery that enormous amounts of atomic energy can be released by the fission of uranium nuclei when bombarded with neutrons. The significance of this achievement was discussed at the recent AIEE winter convention by 1938 Nobel Prize Winner Enrico Fermi, who indicated that results of far-reaching significance may be expected from further experiments (*pages 57–8*).

News Section Rearrangement. Beginning with this issue, the material in the news section of ELECTRICAL ENGINEERING has been divided for the convenience of the reader into two main sections, one containing news of Institute activities, and the other items of interest about the electrical industry, engineering education, other societies, and related matters. Key subject headings within the divisions serve as further guides to the reader. Members are invited to comment on the change (*pages 84-92*).

Science in the Electrical Industry. The story of the electrical industry is one of growth in giant breath-taking strides and great technical advances. Behind this growth, the rate of which has shown no diminution since the birth of the industry, lies a significant, important fact, says an executive of one of the leading electrical manufacturing companies: "The industry has consistently accepted and adapted to its own use the new ideas and developments of science" (*pages 63–7*).

Telegraph Switching. A telegraph relay office must be provided with means for storing the incoming signals without delaying their reception, for moving them immediately from the incoming to the outgoing circuit terminals, and for retransmitting them as soon as the outgoing circuit is clear; the latest switching system requires only one-quarter of the time of manual operation (*Transactions pages 71–8*).

Progress in Machinery. Between 1934 and 1939, substantial progress was made in various branches of the art in electrical machinery; outstanding items are turbine generators of large ratings operating at 3,600 rpm, and the application of hydrogen cooling; use of glass insulation; and sealed-off mercury-arc rectifiers (*Transactions pages 103–06*).

Use of Federal Water Power. Large quantities of electric power are becoming available at the extensive Federal irrigation and hydroelectric projects. The electrochemical industry is said to be the only one that can absorb this power. Suitable raw materials for various electrochemical processes are available at or near all of the new power sites (*pages 59–62*).

Capacitor Timing. A capacitor and resistor in series may be used as a timing device that has already been applied widely for resistance-welding control, and which now is extended to motor control; the availability of large capacitors eliminates the need for amplifiers (*Transactions pages 65–70*).

Potential Devices. New theoretical methods, introducing an equivalent circuit, have been devised for the analysis of the transient and steady-state performance of potential devices of the capacitor type; field, laboratory, and network-calculator tests have been made for verification (*Transactions pages 91–102*).

Electricity and Petroleum. Design and operation of oil refineries have been affected by improvements in electrical apparatus, as electric power is combined with steam in order to obtain the greatest possible economy; explosive and corrosive gases have required special consideration (*Transactions pages 106–10*).

Illumination Modernization. By installing luminaires of a newly developed design, the illumination level in a drafting room of a large eastern power company was increased 150 per cent over that obtained with the replaced system, with an increase in power consumption of less than 60 per cent (*pages 68–9*).

Watt-Hour Meters. A peculiar state of vibration has been found to exist in the moving system of an a-c watt-hour meter when only the potential element is excited, which has been found by experiment to result in a total travel of the meter pivot approximately ten times as great as the travel at full load (*Transactions pages 116–22*).

Oilless Circuit Breaker. Using water in place of oil, circuit breakers for 15 kv have operated satisfactorily in service at a rating of 500,000 kva, and development has been carried to a rating of 1,500,000 kva. Outstanding advantage is the noninflammability of the interrupting medium (*Transactions pages 111–16*).

Breakdown in Oil. Knowledge of the breakdown of gaps submerged in oil and subjected to surge voltages is desirable for circuit-breaker design, and some now has been obtained by use of a specially constructed test barrel (*Transactions pages 78–84*).

Transformation Theory. Equations for general static polyphase networks may be obtained from the canonical equations of a general linear bilateral network with a minimum of algebraic work by the application of transformation matrices (*Transactions pages 123–8*).

Ground Protection. If radial distribution feeders are to be cleared when a ground fault occurs, a sensitive protective means is necessary because contact conditions at the fault may permit only a small current to flow (*Transactions pages 84–90*).

Coming Soon. Among specia larticles and technical papers now undergoing preparation for early publication are: an article on distribution systems in buildings, by L. W. Moxey, 3rd (A'30); an article on the status and trends of engineering education in the United States today, by Dugald C. Jackson (A'87, F'12); an article presenting a summary of bridge networks, by Walter J. Seeley (A'19, M'28); a paper describing a new type of d-c to a-c vibrator inverter, by O. Kiltie (A'31); a paper describing a new technique for lead cable sheathing, by B. B. Reinitz and R. J. Wiseman (F'27); a paper on radio - frequency high - voltage phenomena, by Andrew Alford and Sidney Pickles (A'37); a paper on instruments and methods of measuring radio noise, by C. V. Aggers (A'39), Dudley E. Foster, and C. S. Young; and a paper describing a direct-acting generator voltage regulator, by W. K. Boice (A'39), S. B. Crary (M'37), Gabriel Kron (A'30), and L. W. Thompson (A'39).

Subscriptions—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii, Philippine Islands, Central and South America, Haiti, Spain, Spanish Colonies; $13 to Canada; $14 elsewhere. Single copy $1.50. ¶ Address changes must be received by the 15th of the month to be effective with the succeeding issue. Copies undelivered because of incorrect address cannot be replaced without charge. ¶ ELECTRICAL ENGINEERING is indexed annually by the Institute, weekly and monthly by *Engineering Index*, and monthly by *Industrial Arts Index*; abstracted monthly by *Science Abstracts* (London). Copyright 1940 by the American Institute of Electrical Engineers. Printed in the United States of America. Number of copies this issue 23,150.

Nuclear Disintegrations

ENRICO FERMI

The fission of uranium, in which the uranium nucleus splits into two fragments of comparable size, achieved during 1939 by bombardment of uranium with neutrons, has stimulated great activity in this field of research and may lead to further research of fundamental and far-reaching importance.

MUCH of the information available at present on the structure of atomic nuclei has been gathered by a successful application of the technique of the so-called nuclear bombardments. This technique, initiated about 20 years ago by Lord Rutherford, consists in hurling against the nucleus a projectile (originally this was one of the alpha particles spontaneously emitted by radioactive substances) and in observing the changes in the nuclear structure produced by the impact. In the last years this technique has received new impetus due, on one hand, to the development of artificial sources of high-energy projectiles (high-voltage apparatuses and cyclotrons) and, on the other hand, to the discovery of the neutron.

Several hundreds of different artificial nuclear disintegrations have now been investigated. Their study has led to the development of the so-called nuclear chemistry in which, instead of changes of aggregations of atoms to form different molecules, as in chemistry, changes in the aggregation of neutrons and protons to form different nuclei are observed. This nuclear chemistry obeys rather simple rules, and the different types of nuclear reactions can be summarized as in the following paragraphs.

Nuclei have been bombarded so far mostly with the following types of projectiles: alpha particles, protons, deuterons, and neutrons. Whenever one of these particles strikes the nucleus it is incorporated into the nuclear structure, and another particle may be emitted which belongs to one of the same four types. In a few instances nuclear reactions have been produced by hard gamma rays or by high-energy electrons. We have further to add the many cases of radioactivity, both natural and artificial, in which an unstable nucleus spontaneously emits an alpha particle, or an electron (negative or positive). The residual nucleus that remains after the reaction is always different from the one before the impact. In general, however, the changes in atomic weight, or atomic number, are not very large. Indeed, the greatest changes in atomic number occur when an alpha particle is either absorbed or emitted in the process. Since the electric charge of the alpha particle is of two units, this produces a displacement in the atomic number of two places only.

In many cases in which a chemical identification of the reaction products of nuclear bombardment has been possible, it has been found consistently that the reaction products are either isotopes of the original element bombarded, or they differ from it in atomic number by only a few units. There was, therefore, a great sensation among nuclear physicists last year when Hahn and Strassman announced that by bombardment of uranium (atomic number 92) with neutrons, they had found definite evidence of the formation of some radioactive isotopes of barium (atomic number 56). Such a change by 36 units in the atomic number had never been considered possible before; subsequent investigation has shown that it corresponds to a nuclear reaction of an entirely new kind, in which the uranium nucleus splits into two fragments of comparable size.

This discovery of Hahn and Strassman has opened a very interesting new field of investigation. It is well known that all the heaviest elements of the periodic system are to some extent unstable, as is shown by their natural radioactivity. The physical reason for this instability is the electrostatic repulsion between the positively charged constituents of the nucleus. These repulsions are approximately proportional to the square of the nuclear charge and, therefore, increase considerably with increasing atomic number. Instability sets in when the electrostatic destructive forces overcome what we may call the cohesive forces of the nucleus.

The theory of nuclear forces is not yet developed so far as to enable us to calculate exactly at what value of atomic number instability sets in. Probably, however, this limit is not far beyond 92, the atomic number of uranium. The discovery of Hahn and Strassman shows, indeed, that in the case of uranium the relatively unimportant perturbation of the nuclear structure due to the capture of a neutron is already sometimes sufficient for breaking into pieces the nucleus, giving rise to the so-called fission process.

A pictorial image of the process has been suggested by Bohr, who compared this process with what happens when a liquid drop divides into two smaller droplets as a consequence of a very strong oscillation in which it changes

Essential substance of an address delivered at a special session of the AIEE 1940 winter convention, January 24.

ENRICO FERMI, distinguished physicist and winner of the 1938 Nobel Prize in physics, is now associated with the department of physics, Columbia University, New York, N. Y., where he is engaged, with others, in research on nuclear physics.

from the original spherical form into an elongated shape. In the case of uranium, however, as soon as the two fragments are separated and the cohesive forces cease to attract them, the strong repulsion due to both fragments being positively charged, pushes them apart, impressing on them a relatively enormous kinetic energy. In fact, the amount of energy released in the fission process is approximately ten times greater than any amount of energy released in atomic disintegrations, it being of the order of 200 million electron volts. (An electron volt is defined as the amount of energy gained by an electron in passing from a point of low potential to a point one volt higher in potential.) Although the discovery of this process is only one year old, a great many investigations have been carried out in laboratories all over the world, so that a general description of the main features of the phenomenon is now possible, in which, however, many important details are still missing.

The fission process can be produced by bombardment with fast neutrons having energy above one million electron volts, and by slow neutrons, having energy corresponding to thermal agitation equivalent to a small fraction of an electron volt. Neutrons of intermediate energy are rather inefficient as agents for producing fission. It has been pointed out, especially by Bohr, that this fact might possibly be interpreted on the assumption that the fast-neutron and the slow-neutron process are due to two different isotopes of uranium. Probably the fast-neutron process is due to isotope 238, which represents more than 99 per cent of natural uranium, whereas the slow-neutron process might be attributed to a much rarer isotope of weight 235, which is known to be present in an amount somewhat less than 1 per cent and is the parent substance of the actinium radioactive family. No direct experimental information on this point, which is of considerable importance both from the theoretical and the practical point of view, is at present available.

Each fragment into which uranium splits in the fission process weighs approximately one-half of the original nucleus. Apparently, however, the fission does not always occur in exactly the same way, and there are certain limits between which the weight of the fragments can vary. Since each fragment gives rise to several artificially radioactive nuclei, it is clear that the fission process will produce a large variety of new radioactive elements. An extensive chemical investigation of these elements has been carried out in several laboratories and has already led to the identification of more than 20 such elements, but the list is probably still far from being complete.

When uranium undergoes fission some neutrons are emitted. It has not been decided so far whether these neutrons are emitted in the very act of fission, or a very short time after the process. The two fragments into which uranium splits get away with a very high internal excitation. The excitation energy might be so large as to produce the spontaneous emission of neutrons from the two fragments. The largest part of this emission of neutrons certainly occurs within an exceedingly short time after the fission; the emission of a small number of neutrons, however, lasts for some seconds after the fission process. This delayed emission of neutrons is probably a secondary process of some beta disintegration.

The emission of neutrons is not only an interesting feature of the phenomenon, but might perhaps be of far-reaching importance, as it opens at least one possibility of exploiting the fission of uranium for the production of nuclear reactions on a large scale.

Let us assume for a moment that in every fission process two neutrons are emitted (actually experiment shows that probably the average number of neutrons emitted is somewhat larger, between two and three). If this were so every neutron that enters the uranium nucleus and produces fission would give rise to two neutrons with the net gain of one. If we assume that these two neutrons again produce each one a fission we get at the end four neutrons from the original one. Any one of these four neutrons might again produce a fission, multiplying the number of neutrons once more by two, and so forth, until the number of neutrons might in principle be multiplied by an arbitrarily large factor, thus giving rise to a self-perpetuating nuclear reaction—the so-called chain reaction. In order that the chain reaction might occur, it is obviously necessary not only to have more than one neutron produced for every neutron that is absorbed in the process of fission, but also to be able to utilize for producing new fissions a large faction of the neutrons produced; otherwise the loss might be larger than the gain.

Assuming, as before, that two neutrons are produced in every fission, it is evident that for the chain reaction to take place more than one-half of the neutrons produced must be used in new fission processes. There is now, on one hand, some loss of neutrons that diffuse outside of the reacting mass before they have a chance to react. This loss can be made, at least in principle, arbitrarily small, by increasing the amount of the reacting material. On the other hand, some of the neutrons are lost for the reaction because they are absorbed by uranium itself in a second process, which does not lead to fission but to the formation of a heavy radioactive isotope of uranium. Some absorption is finally due to those substances that must be present in order to slow down the neutrons, so as to increase their aptitude to react with uranium. Whether these absorptions are, or are not, sufficiently large to prevent the chain reaction, cannot be answered at present. The experiments require the use of very large amounts of both uranium and "slowing-down" materials and are, therefore, very expensive. The problem seems to me, however, worth the effort that its solution will cost. There is indeed a chance that research on these lines might open entirely new technical opportunities, whose range at present can only be guessed. The large release of energy by the reaction, whose development, by the way, could be easily controlled by simple mechanical devices, is indeed probably only one and very likely not the most important aspect of the problem. Far more important might eventually prove the production of radioactive materials and of neutrons in practically unlimited amounts, for medical, biological, and physical investigations. In conclusion, although there is only a chance of success, the stake appears large enough to justify some gambling.

Federal Water Power and Electrochemical Industries

COLIN G. FINK

The electrochemical industry is said to be the only one that can absorb the large quantities of electric energy soon to become available from the many Federal irrigation and hydroelectric projects. As suitable raw materials for various processes are available at or near all of the new power sites, the construction of one or more electrochemical plants at each of the new centers has been advocated, which will result in an increasing demand for engineers conversant in both electrical and chemical engineering. Young engineers now obtaining their training are urged to fit themselves to take advantage of these opportunities.

AN INTERESTING situation has arisen in consequence of the extensive Federal dam projects that have been under way for some years. Basically the Boulder, Bonneville, Grand Coulee, Norris, and other dams were developed for other purposes, electric power being "merely" a by-product. The problem that is of special interest to engineers, in particular to electrical and chemical engineers, is what is to become of the large quantities of power remaining after all requirements for domestic uses, lighting, and mechanical power have been amply provided for. This question has been carefully and thoroughly discussed by experts in both the power and the electrometallurgical fields and the unanimous conclusion reached is the one recorded in the recently published detailed report of the United States Federal Power Commission:[1–3] The electrochemical industry is the only one in position to absorb this vast by-product power ultimately available upon completion of the various irrigation projects now under way. The by-product power will total more than 2,000,000 kw, a goodly proportion of which is far from the main manufacturing centers or markets for power.

There is hardly any need to discuss the fact that electric power is cheapest when generated at or near the place of consumption. Furthermore, it has been pointed out repeatedly that "the trend in power-cost reduction is in the direction of less expensive and better operating fuel-burning plants—not toward Diesels or hydroelectric plants".[4] The experience of the Pacific Gas and Electric Company is too well known to need repetition here.

At all events, with low price and steam-electric power available in most of the present manufacturing centers, what solution have we to offer as to the utilization of the excess power derived from the Government irrigation projects?

Transmitting electric power to manufacturing centers several hundred miles away is costly—much more costly than transporting fuels to these centers. Admitting that under present conditions and with present means power transmission to any great distance, say beyond 250 miles, is highly uneconomical as compared with the transportation of fuels, it may very well develop, as Doctor Karl T. Compton, chairman of the Science Advisory Board, announced five years ago, that entirely new methods of transmission, such as the evacuated pipe line, will make it feasible to transmit electric power to towns and industrial centers many hundreds of miles distant from generating stations.

But even with very low transmission costs, we are ultimately confronted with the fact that the many thousands of kilowatt-hours, soon to become available, must be absorbed in electrochemical industries.

Raw Materials

As to raw materials for the production of aluminum, ferroalloys, magnesium, and other electrochemical products, there are deposits, some very extensive, of a large variety of ores in widely distributed localities in the country. Thus, for example, very large deposits of phosphate rock, suitable for electric-furnace conversion into

Address presented at a meeting of the AIEE New York Section, November 14, 1939.

COLIN G. FINK is professor of electrochemistry, Columbia University, New York, N. Y.

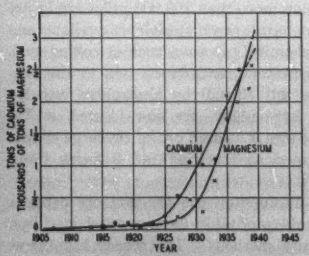

Figure 1. Production of magnesium and cadmium in the United States

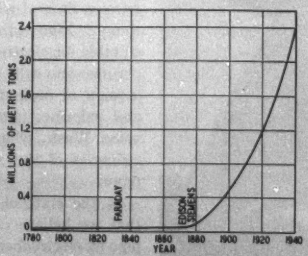

Figure 2. World's production of copper

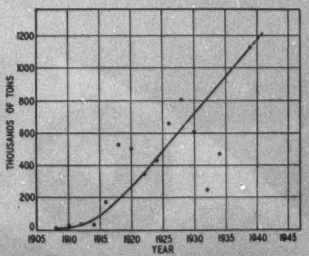

Figure 3. Production of electric furnace steel in the United States

phosphate fertilizers, are located in Idaho, Wyoming, Utah, and Montana. We are no longer limited to the use of high-grade phosphate rock. As a result of discoveries and advances made in flotation we can concentrate low-grade phosphate material into grades suitable for the electric furnace.

Magnesite, native magnesium carbonate, is found in California and elsewhere. Magnesite is the raw material for the new electric-furnace process for the production of magnesium by reduction and volatilization—possible only through high electric heat. The heat of formation of magnesium oxide (MgO) is 610 kilojoules as against 146 for copper oxide (CuO).

A mixture of dead burned magnesite ($MgCO_3 \rightarrow MgO$) and coke is fed between electrodes of a 2,400-kw three-phase electric furnace. The furnace is of the closed or sealed type, and the entire charge is volatilized at a temperature approximating 2,300 degrees centigrade. The reaction $MgO+C=Mg+CO$ is reversible, and upon *slow* cooling we get back MgO. However, if the magnesium vapor together with the carbon monoxide, as they leave the furnace and pass through a pipe to the condenser, are suddenly chilled by injecting a large volume of hydrogen, then the reformation of MgO is prevented, and magnesium metal collects in the condenser. This electric-furnace process is competing with the older fused-magnesium-chloride process.

The magnesium industry has had a phenomenal growth during the last few years, as the curve in figure 1 illustrates. The supply of the metal has exceeded the demands of the automotive industry. Dow Metal, the trade name for the most important magnesium alloy, has found numerous uses, such as I beams and other structural materials, airplane parts, motor fans, foundry flasks, motion-picture cameras. The aircraft industry consumes more than half of the total magnesium produced.[5]

Deposits of low-grade manganese ore suitable for the electrowinning of manganese are located near several of the new power sites. A recently established electrolytic manganese plant is at Knoxville, Tenn., next to the Government-built Norris Dam and close by the Tennessee manganese-ore deposits. The process[6] here applied is that of leaching native low-grade high-silica manganese ore with acid-ammonium-sulphate solution and electrodepositing manganese at the cathode. A recent improvement in the process[7] eliminates the loss due to manganese peroxide formation at the anode by catalyzing the evolution of oxygen in preference to the formation of manganese peroxide. We are fully confident that this new electrolytic process, as it is amenable to our poor-quality native ores, will make the United States independent of high-grade imported ores—emanating from Russia, South Africa, Brazil, and elsewhere, and constituting today about 95 per cent of domestic consumption.

Tungsten ore for the electric-furnace production of high-speed steels and other important alloys is found in a dozen western states. The largest producer is Nevada, the home of Boulder Dam. In Nevada, too (Humbolt County) are found high-grade alunite deposits suitable for the electrolytic production of aluminum.

The world's aluminum production has doubled during the last ten years, just as it did in the previous ten years (see table I). The demand for the metal is ever increasing, for such uses as: airplane engines and bodies; street cars and streamlined trains; locomotive cabs (3,000 pounds lighter than steel cabs); and high-voltage transmission lines of which more than 700,000 miles are in use today. Many other native raw materials are available and suitable for electrochemical processes such as coking coal, chrome ore, salt, limestone, and fluxes. As to the conversion of ordinary salt (NaCl) by electrolysis into lye and chlorine, two large plants are now located at Tacoma, Wash., where also is located one of the large copper refineries of the American Smelting and Refining Company.

In the state of Washington too are iron ore deposits that we believe could profitably be converted into iron pipe by electrochemical methods. This scheme is not new. Two French engineers, Boucher and Bouchayer, produced thin-walled iron tubes at Grenoble for a number of

Table I. Annual Electric-Energy Consumption by a Few of the Electrochemical Industries (World Output)

Product	Thousands of Tons Produced			Millions of Kilowatt-Hours Consumed		
	1919	1929	1939	1919	1929	1939
Aluminum	150	300	600	3,700	7,000	13,500
Copper (electrolytic)	900	1,800	2,200	250	600	730
Zinc (electrolytic)	70	500	600	240	1,500	1,800
Caustic and chlorine	150	400	2,400	400	1,140	7,000
Calcium carbide	900	1,600	2,600	2,520	4,160	6,200
Electric steel	800	2,200	2,500	480	1,100	1,200
Ferroalloys	220	550	600	1,320	3,000	3,300
Abrasives*	50	150	180	280	750	900
Total of products listed	3,240	7,500	17,080	9,190	19,290	34,630
Estimated grand total†	3,500	10,000	23,000	10,000	21,000	39,000

* Silicon carbide and artificial emery.

† Includes products not listed, such as graphite, nickel, chromium, lead, silver, gold, cadmium, magnesium, sodium, phosphorus, carbon bisulfide, hydrogen, and oxygen.

Figure 4. Die castings of magnesium alloy

Courtesy Dow Chemical Company

Courtesy Dow Chemical Company

Figure 5. Sand-cast aircraft-engine parts of magnesium alloy

years. Figure 7 shows a section of pure-iron pipe nine inches in diameter with a one-quarter inch wall, which was made at the Columbia University laboratories. A new chloride solution was developed that served as electrolyte.[8] The cathode was a steel mandrel rotating at a peripheral speed of about 350 feet per minute. Pure iron was deposited at a current density of 100 amperes per square foot. Cost estimates for 30-foot pipe on the basis of five-mil power indicate that electrolytically deposited pipe is decidedly cheaper than drawn pipe. Another factor that favors electrolytic pipe is the ease with which iron ore can be leached—in this way dispensing with furnace operations entirely.

Markets

There is no question as to availability of cheap electric power at the irrigation-project centers. Nor is it primarily a question of availability of raw materials for various electrochemical processes. Many engineers believe that the immediate question is that of *markets*. Will it be possible profitably to dispose of aluminum or magnesium or calcium carbide made in Oregon or in Washington, or in Nevada, or in Tennessee? Frankly, I am of the belief and opinion that, after the establishment of the new electrochemical centers, the markets are bound to follow. To set up an alkali-chlorine plant at Tacoma would have been considered a very foolhardy undertaking a generation ago. Yet today the two plants at Tacoma are turning out 20-odd different products and selling them.

The Aluminum Company of America has just recently signed a contract for the use of Bonneville hydroelectric power. The contract calls for 32,500 kw. A 200-acre plot has been acquired in Vancouver, Wash., and the new electrochemical plant to be built will have an initial producing capacity of 15,000 tons of aluminum per annum. The standard fused-electrolyte process of Hall will be used which requires as much as 11 kilowatt-hours per pound of aluminum produced (table I).

In discussing this question of markets for electrochemical products that will be made at these new hydroelectric centers, it may be interesting to recall the birth and development of the automobile-manufacturing center at Detroit, Mich. As has been fittingly and repeatedly stated, "Niagara Falls made Detroit possible"; in other words, without the electric-furnace products such as ferroalloys, abrasives, and others made at Niagara Falls, the automotive industry would not have progressed as rapidly as it has. Without electric-furnace products the modern automobile would be nonexistent. Yet it was necessary during the early years of the automotive industry (and to a large extent still is) to ship ferroalloys from Niagara Falls to the steel centers at Pittsburgh, Pa., and elsewhere and from there ship the various alloy steels to Detroit—a total distance of 400 miles—before final utilization in an essential component of the automobile.

Just as our Government at Washington has been confronted with the problem of water-power utilization, so likewise has London been studying the utilization of the huge power of Victoria Falls in Northern Rhodesia, Africa, the potentialities of which exceed by far those of Niagara. From 20 to 60 million gallons of water daily has been passing over the brink of Victoria Falls for 85 years since their discovery by David Livingstone. And it was only a year or so ago that the first step was taken to utilize even a very small fraction of the power. In March 1938, a 4,000-kw hydroelectric plant was completed. The first two of the four units are in operation and are supplying electric power to the nearby town of Livingstone for lighting and motor requirements.[9] This is a small beginning—4,000 kw at

Figure 6. De-icer-fluid tank for aircraft, fabricated from magnesium-alloy sheet

Courtesy Dow Chemical Company

Victoria Falls as compared with 1,200,000 kw of generated and consumed hydroelectric power at Niagara Falls—yet British engineers are fully aware and hopeful of the possible future developments.

Sir Alexander Gibb, past president of the British Institution of Chemical Engineers stated[10] rather pointedly: "Niagara now offers every facility to the manufacturer except really cheap power; and isolated and almost inaccessible Canadian sites are in consequence being exploited in preference by those who can afford to do so. . . . The electrochemical load is the basis of the economical production of electricity, and economically produced power is a *sine qua non* of the electrochemical industry. To the interaction of these two interests has been due more

than to anything else the great development of cheap power."

Africa's potential water power is threefold that of North America; and her mineral resources outstrip those of any other continent: copper, phosphates, chrome ore, gold, manganese, radium, cobalt, asbestos, and others. I can foresee a great electrochemical future for Africa.

Conclusion

In conclusion there is just one other factor these new electrochemical centers at the various dam sites will have to reckon with, and that is the supply of engineering talent. Young men are needed who not only are conversant with the electrical features of electric furnaces, electrolytic

Figure 7. Section of pipe made by the electrodeposition of iron on a steel mandrel

cells, fused electrolytes, and other electrochemical apparatus, but these men must be familiar with the chemistry of the reactions involved; they must be able to sample an electric-furnace heat and in a few minutes determine whether or not the product meets with the close specifications laid down by the consumers. Not only must these young men be electrical engineers, they must be chemical engineers as well.

Here lies an opportunity for the young engineers entering our universities today: They should so select their course of study as to fit them for the new electrochemical plants that are bound to spring up in various sections of the country. With the active support of the young engineers, the electrochemical industry in America is bound to go forward with even greater strides than it has in the past 30 years.

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Paint Reflection Tests With Mercury and Incandescent Lighting

RESULTS of a series of tests made on surfaces painted with 21 different commercial interior tints, under both mercury and incandescent illumination, should prove helpful in selecting colors for use with various types of lighting equipment. The tests were made by the lamp division of Westinghouse Electric and Manufacturing Company, under the supervision of S. G. Hibben (A'34) director of applied lighting.

White had the highest reflection value of the 21 light tints tested, indicating that with indirect or semi-indirect lighting equipment which casts much of the light upward, white should be used for ceilings. Colors for interiors should be chosen not only for reflection value but with consideration of the wave lengths normally predominant in the output of the type of illumination used. The continuous spectrum of the filament lamp is relatively deficient in the blue-violet end of the spectrum; that of the mercury lamp, in the red end.

The basic standard of comparison for the tests was a surface of magnesium carbonate with a reflection coefficient of 98 per cent. The illumination from the filament lamp corresponded to that of the medium-wattage Mazda lamps in ordinary store or office use. The mercury illumination was from a standard 250-watt high-intensity mercury-vapor lamp at about one-half atmospheric pressure, operated at a stable temperature and normal rating. Illumination in all tests was diffuse.

The tests showed the average coefficient of reflection for the 21 colors to be about two per cent higher under mercury illumination than under incandescent. For mercury the average was 0.679; for incandescent, 0.657. "Satin white," the tint with the highest reflection value, had a coefficient of 0.87 for mercury lighting; 0.85 for incandescent. However, pinks, buffs, tans, and reddish tints had slightly higher reflection values with incandescent illumination than with mercury.

To determine comparative reflective values, the 21 tints were divided into three reflection coefficient groups: above 75 per cent, 60 to 74 per cent, 45 to 59 per cent. Under incandescent light, each group contained seven tints. Under mercury light, the groups shifted, the first containing only four tints, the second ten, and the third, which corresponded with only one exception to the same group under incandescent lighting, seven tints.

The Role of Science in the Electrical Industry

M. W. SMITH
MEMBER AIEE

Behind the phenomenal growth of the electrical industry lies an important fact: "The industry has consistently accepted and adapted to its own use the new ideas and developments of science."

THE STORY of the electrical industry is one of growth in giant, breath-taking strides and great technical advances. Turbine-generator units have progressed to the stage where ratings of 100,000 kva at 3,600 rpm and 300,000 kva at 1,800 rpm can now be built. Hydraulic generators, the size of which may ultimately be limited by manufacturing facilities because of their large diameters, have exceeded 100,000-kw rating. Efficiencies of some of the large hydrogen-cooled turbine generators, synchronous condensers, and frequency changers have approached 99 per cent in individual units. Transformers have increased to present-day ratings of over 150,000 kva per bank, and efficiencies of well over 99 per cent have been realized. Circuit breakers are capable of interrupting several million kilovolt-amperes—equal to that of the short-circuit capacity of some of the large interconnected systems. Lightning arresters are available with sufficient capacity to handle a direct lightning stroke of over 100,000 amperes and yet limit the voltage to safe values.

Behind this growth, the rate of which has shown no diminution since the birth of the industry, lies a significant, important fact. The industry has consistently accepted and adapted to its own use the new ideas and developments of science. In fact the industry has fostered and encouraged fundamental research to the point that the research laboratory has become an integral part of the industry itself. It also recognizes the value and importance of the scientific accomplishments of the universities and other research institutions, and maintains a close contact with their work.

Although the industrial laboratory has become the basic element in the electrical industry, the manner by which its fruits are put to practical use is complex. Not only are there many ways by which a new idea is transformed into a practical thing, but also there are many problems in connection with making the fullest use of scientific effort. These ways and these problems merit a closer examination.

Efficient Use of Science Presents Many Problems

The task of the industry is not only to uncover new principles and make new discoveries, but also to determine which ones can be put to practical, profitable use, and how. It is difficult to recognize the potential value of new discoveries and to determine at an early stage the possibilities of applying them to industrial processes and products.

The Problem of Timing

The rate of application of new ideas is not dependent solely upon the time necessary to conceive and develop them. It is also influenced by the time required for public acceptance. Household refrigeration, the basic principle of which is very old, required a relatively long time for both instrumentalities and public acceptance. Numerous problems had to be solved in the commercial development of such items as suitable refrigerants; sealed compressor shafts or the alternative of hermetically sealed units; systems of proper lubrication that would be effective for a period of years; elimination of noise; quantity production methods such as those previously developed in the automobile industry; electric-welding methods; and many other items, including even such things as a system of time payments.

During the first two decades of radio the efforts of radio engineers were directed toward developing methods by which radio could be used as a means of private communication. It remained for a new idea, the opposite of this notion, to allow radio to assume its present stature. Public acceptance of radiobroadcasting was almost instantaneous. This case is an exception to the rule that the exploitation of new products and devices usually results in unprofitable operation for prolonged periods.

The course of carrier current also supports this point. In the middle 20's carrier current came into successful use for communication along transmission lines. Then came a quiet period of several years in its development, followed about 1935 by an intensified activity which shows no signs of any immediate slackening. The need for high-speed relaying of long lines, the development of better tubes, and other changes in the industry spurred engineers to adapt the fundamentals of carrier current to relaying and supervision as well as communication.

Spot welding has been a practical, though limited, industrial tool for many years. However, some six or eight years ago, the idea was conceived of using the ignitron to control exactly the duration of the welding current. Since that time, spot welding has grown enormously both in total use and in diversity of applications. The ignitron,

M. W. Smith is vice-president in charge of engineering, Westinghouse Electric and Manufacturing Company, Pittsburgh, Pa.

incidentally, was originally developed not with welding in mind but to increase the reliability of mercury-arc rectifiers.

The Problem of Obsolescence

The industrial laboratory poses the inexorable problem of obsolescence. Fortunately the leaders of the electrical industry have taken the farsighted view that, in order to make sound progress, the seeming ruthlessness of obsolescence must be accepted. Unless one has studied the rates of development and consequently the rates of obsolescence, it is seldom realized how relentless is the march of progress.

A plant that is modern today may be out of date tomorrow. As a matter of fact, the more progressive companies attempt to anticipate obsolescence. Capital expenditures are made on the basis of the time at which the new plant or equipment will be obsolete, not when it is worn out.

The discovery of a new fact in science may completely upset an existing design. Even though the style or performance of a product may not be greatly modified, the practice of the art or process by which it is produced may be radically changed. With the steep rise of welding not long ago, in a few short years the method of constructing most large machines swung from casting to welded fabrication. Neither the appearance nor the performance of the machines was fundamentally altered by this change; the principal motive is economy of time and of construction cost.

It behooves all managements to keep themselves keenly alive to the necessity of meeting changes resulting from progress. Of all competition, there is none quite so ruthless as that which replaces. We all can remember that during the early stages of radiobroadcasting, several plants rapidly grew up for the making of radio headsets. The development of the loud-speaker practically ruined this active business. The early sets used vacuum tubes supplied by direct current, requiring plate and filament batteries. This created a heavy production of dry batteries that was subsequently curtailed by the development of plate-battery eliminators. Later, the development of the copper-oxide rectifier eliminated the use of the storage battery for filaments, and still later, the development of a-c tubes so completely changed the design of radio receivers that it rendered many inventories and factory equipments obsolete.

The most recent step in this evolution—and one that shows the cyclic character of many industrial developments—is the battery-operated portable set that has suddenly become so popular. It is additionally significant that although a tube development displaced the early battery set, another development of tubes brings the battery back—the perfection of a tube that operates successfully on $1^1/_2$ volts.

This last development also shows the rewards from the policy of letting the obsolescence caused by science take its seemingly ruthless course. The new battery-operated radios do not offer new competition for established types of radio sets, but instead simply create or uncover an additional demand for radios. The demand for batteries and for tubes promises to reach an all-time peak.

Similar successive steps of development occurred in illumination. A large kerosene-lamp industry was rendered obsolete, particularly in metropolitan districts, by the coming of the gas mantle. It, in turn, was replaced by the electric lamps. Now a new family of lamps—the gas-discharge lamps, which include sodium-vapor, high-pressure mercury-vapor, and fluorescent units—with efficiencies several times those of incandescent lamps, have demonstrated their practicability. It is still too soon to predict to what extent they will become the universal illuminants, but there is more than a hint that illuminant evolution is not at an end. No one in the industry thinks for a minute that the more efficient light sources presage a decrease in the requirements for energy or equipment. On the contrary, as in the past, this improvement should promote further expansion.

Industry Finds Many Benefits From Organized Research

The industrial laboratory has served the march of electrical progress in many ways. Not the least of these is that it has served to bring the scientist, the design engineer, and the application engineer into closer contact. They now talk the same language and use the same tools. Universities are giving more attention to the training of industrial scientists, and, within the last few years, important meetings have been devoted to discussions of the application of physics to industry.

The co-operation of university and industrial scientific effort has also contributed much to the progress of development by bringing scientists of different training closer together on specific problems. For instance, much of the recent progress in the improvement of insulation for electrical apparatus has resulted from the combined efforts of physicists, chemists, and electrical engineers working harmoniously in close-knit groups. For many years, only a limited number of scientists in the universities had shown any interest in dielectrics, particularly solids. The engineer stumbled along rather blindly, and little progress was made until all phases of the problem were co-ordinated through the industrial laboratory. This relationship not only has served an important function in co-ordinating the efforts of individuals, but also has exerted a strong influence in bringing together the various departments within an organization as well as outside agencies on problems of mutual interest. A new development for one department is often seen to be of value to another. Thus, research acts as a clearing house for information and stimulates its flow from one department to another.

Joint Research Between Manufacturer and Supplier

Another co-ordinating function of the industrial laboratory is the co-operative work between electrical manufacturers and the suppliers of raw materials. For many years, electrical manufacturers have carried on co-opera-

tive research with manufacturers of steel, carbon brushes, insulating materials, and other raw materials. As a result greatly improved materials have been developed. These in turn enable the electrical manufacturer to build more reliable and more efficient apparatus, which can be extended into new and larger fields of application.

Industrial Research Shortens Time Between Discovery and Use

Another important accomplishment of the industrial laboratory has been to effect a marked reduction in the time between the discovery of a new idea and its commercial application. For example, only a few years ago scientists conceived the idea of using as a germicidal agent a certain type of lamp the rays from which are lethal to bacteria. In the last two or three years the resulting Sterilamp has been put to regular daily use in tenderizing meat, retarding spoilage of foods, killing bacteria on drinking glasses, helping to prevent infection following surgical operations, and many other important tasks.

Even today, however, special attention must be given to this phase of the problem: After the research work has been completed and the theory or principle of operation has been verified, there still remains the decision as to the commercial possibilities of the new device or product. Usually sufficient information is not available at this stage on which to base an intelligent decision. Information as to probable costs (including equipment investment), processes, production methods, market analyses, and distribution methods must be obtained before a decision to manufacture and sell can be made. This requires that the new product be carried through some preliminary stage of development, where a study of these factors is made. Usually this takes the form of some kind of pilot-plant activity under the direction of a special experimental or development group that has the responsibility of carrying new products through this incubation stage following the completion of research work. This form of development is particularly conspicuous in the chemical industry.

Patent System Stimulates New Developments

Our patent system has had a stimulating influence on industrial research and developments in the electrical industry that should not be overlooked. It costs money to develop and exploit inventions. The protection afforded by patents provides an incentive to develop new things under conditions such that they may be exploited long enough to become established. Quite often a strong urge toward a particular development seems to become manifest and inventive effort starts simultaneously in many places. This seeming chaos that theorists would like to control from some central throne eventually turns into true co-operative effort through the practical necessity for cross-licensing of patents before a useful product can be obtained. Television is a present-day example. Patents themselves are published and the protection afforded does away with the necessity for secrecy. The new progress that has been made impinges upon other minds, thereby starting new chains of ideas that result in co-ordinated group effort leading to rapid progress.

Without the protection provided by patents, capital would be reluctant to venture into new fields. Industrial research would become secretive, and because of the resulting lack of co-operation and co-ordinated group effort, our progress in technical accomplishments and standards of living would be seriously retarded.

In the light of these advantages, many times verified by experience, it is disturbing to observe the tendency in some political circles to propose legislation that would destroy these values and place serious limitations on individual rights. Even the uncertainties surrounding such proposals create a lack of confidence, tending to retard initiative and technical progress. This same condition exists to a large extent throughout the industry, and particularly in the public-utility field where political threats and limitations have seriously curtailed expansion and thus retarded the use of scientific developments directly in the generation and distribution of electricity.

Electrical Industry Draws From All Basic Sciences

Contributions to the development and progress of the electrical industry have come from practically every branch of the basic sciences. This is not surprising when we consider the large variety of materials used in the manufacture of electrical equipment.

Metallurgy

Improvement in electrical apparatus is largely dependent on the improvement made in the properties of the materials used. This applies to both physical and chemical properties of various kinds. The limitations in physical properties of materials are most likely to be encountered in high-speed rotating machinery such as steam turbines, where centrifugal and steam forces are likely to be large under conditions of high temperature, which in turn tends to lower permissible stress limits.

Research work done in recent years by both electrical and steel manufacturers to determine and improve the fatigue, creep, corrosion, and other physical properties of various alloy steels used in highly stressed machines has resulted in such marked advances in design that output ratings have been more than doubled at the highest operating speeds in less than five years.

The electrical industry has also called on the metallurgist for new and improved magnetic steels and alloys. Magnetic steel, particularly electrical sheet steel, has been a subject of continued research by both electrical and steel manufacturers. This has involved studies of molecular and grain structures as well as of chemical compositions and purity. This work has resulted in a steady decrease in iron losses in the cores of transformers and machines of such magnitude that they have been reduced by more than half in the last 20 years, with a saving to the industry of millions of dollars annually.

Until recently, the improvement in electrical sheet steel was confined largely to iron losses. Practically no improve-

ment in permeability had been accomplished. As a result of recent research and development we now have a magnetic steel that has not only lower iron loss but also much better permeability.

New alloys are sometimes discovered and developed as by-products of other research work. In the electrical industry, the need for new alloys with special characteristics often arises in connection with new electrical developments. It is therefore often necessary to develop special alloys to meet limitations encountered in electrical developments, particularly when the volume required is too small to be attractive to alloy manufacturers. For example, a recently developed alloy containing only a few per cent iron, is stronger at 1,100 degrees Fahrenheit than any low-carbon steel at room temperature. It creeps very little. It survives a 6,000-hour creep test at 1,000 degrees Fahrenheit that causes cast carbon-molybdenum steel to fail and high-strength nickel-chromium steel to creep 100 times as much. As an amazing demonstration of how it retains its elastic properties when hot, a bar of steel and one of this alloy were heated to 1,100 degrees Fahrenheit. When struck with a hammer, the steel bar responded with a dull thud; the alloy with a clear, bell-like tone.

Chemistry

The application of chemistry to the electrical industry has been almost unlimited. Chemists have been called on principally to produce new and improved insulating materials, compounds, varnishes, oils, etc. There have been many other developments, however. For example, a fireproof chlorinated compound has been developed to replace transformer oil in applications where fire hazards exist. Many fireproof liquids have been made available, but a great amount of research and development work has been required in recent years to obtain a material that also had satisfactory electrical properties such as high dielectric strength, low power factor, and viscosities comparable with transformer oil, particularly at low temperature.

Physics

The foundation of the electrical industry is supported to a large extent on the laws of physics. Some of the most important scientific discoveries and applications therefore have come from this field. The discovery of electromagnetism, the electron, and the X ray are outstanding examples. From researches on the mechanics of the ion came the principle of circuit interruption by deionization that has been applied to a whole family of interrupting devices from the giant circuit breakers that handle millions of kilovolt-amperes down to the new practical circuit breakers for the home that are little larger than a wall switch. In the field of electronics, numerous electrical developments of far-reaching importance have been based on these and similar discoveries.

Mathematics

Probably no other industry rests on such a precise mathematical basis as the electrical industry. From its very beginning its every step in the design, construction, and operation of electrical apparatus has been guided by computation. In fact, the electrical engineer has invented several mathematical tools to serve his purposes, such as the complex quantity and symmetrical components. He has even placed his mathematics on a mechanical basis, such as that amazing creation, the calculating board.

Pure mathematical concepts have given birth to many electrical devices. Particularly has this been true of relays for the protection of transmission lines and terminal equipment. A conspicuous recent example is a new, simplified pilot-wire relay that greatly extends the practical field of this type of relaying. This relay was conceived directly from the mathematical conception of positive, negative, and zero-sequence components of alternating currents.

As to the Future

We know so little about nature's basic underlying principles that it is incredible that anyone should think that our knowledge of natural laws is anything but exceedingly small when compared with the vast amount that is listed in the unknown column. This alone should be encouraging, for if we can accomplish all that we have with such a poor understanding, it is reasonable to expect vastly better results as we obtain more basic knowledge.

While our human limitations may prevent us from seeing very far into the future, present developments give us some idea of future trends and in what fields expansions are likely to occur.

In the processing industries, electricity will probably assume an increasingly important role in the way of metering, regulating, and controlling numerous phases of new as well as existing processes. Recent improvements in electric furnaces and their controls, including the control of the atmosphere inside of the furnace as well, indicate various possibilities in this field. For instance, heat treatment of steel sheets for automobiles by continuous processes in less than 15 minutes has been accomplished. In the presence of highly purified atmospheres, various steels and alloys can now be bright-annealed. In controlled-atmosphere furnaces, dies can be heat-treated without oxidization or carburization, thus eliminating subsequent grinding.

In the broad field of air conditioning, electricity will play an important part, not only in applications requiring power but in the processing and treatment of the air itself. Electrical means are now available for cleaning and sterilizing air. These new aids in air conditioning, coupled with the available services of heating, cooling, and humidity control, make it possible to improve man's living conditions so profoundly that he may live in a clean spring or fall atmosphere all the year around in any locality.

Lightningproof electrical systems were but the dreams of engineers a few years ago. They are still not a reality, but the day is coming when they will be. Much has been done in this direction; more is yet to be done. The recent development of a device for recording natural lightning strokes that is relatively inexpensive and simple,

so that dozens of them can be installed over wide areas, will be of tremendous assistance in collecting that quantity of statistical information about lightning necessary for the construction of protective devices and self-protecting apparatus. We now have reason to believe that in the not too distant future lightning, once the great disturber of electrical systems, will be eliminated as a hazard to power continuity.

Vast new vistas are being opened by high-frequency electric energy. High frequencies, which broadly include everything beyond 60 cycles, are already being used for numerous tasks of melting, heat-treating, and drying. Packaged raw materials are being dried without opening the containers; bearing surfaces of finished engine crankshafts are being given additional hardness by localized heating induced by high-frequency currents. With the rapid developments in high-frequency generators, both of the rotating and electron tube types, it is not inconceivable that all gasoline and Diesel engines, machine tools, and other machines will be treated by high-frequency when assembled or partially assembled to harden the wearing surfaces.

The great field of electronics, which is now best known in radio, television, and communication, can be expected to find a greater number of future applications in the electrical industry, particularly in those fields having to do with automatic machine operations, inspection of materials and safety methods. Recent progress in the development of larger and more reliable metal-tank tubes indicates that electronics may also be expected to play an increasingly important part in electric-power distribution, both in transformations and control.

When it is considered that the power consumption in many small homes today is from three to ten times the national average, due to the increasing acceptance of electric ranges, water heaters, forced air circulation, high lighting levels, and other conveniences, we can expect domestic power consumption to double in a reasonable time. This indicates the need for an improved low-voltage distribution system as well as rewiring of homes.

Agriculture is another field that has scarcely been touched by the electrical industry. In addition to the usual applications of power and light, there appear to be many possibilities of applying treatments and radiations for the stimulation of plant growth and control of insects that now infest grains, plants, and seeds.

Present researches in nuclear physics in many institutions may result in obtaining information that will be just as extensive in its influence on the developments in the electrical industry as was the discovery of the electron. The production of radioactive substances, through the disintegration of the atom may provide a very useful tool. Naturally, one thinks of using these radiations instead of the X ray for radiography or for radium in the treatment of disease. While they no doubt will be used to some extent for such purposes, the possibility of using these radiations as a means of studying certain atomic reactions and structures may be even more useful. For instance, by the use of electrical detection methods, it appears feasible to follow the migration of radioactive atoms through a metal during heat-treating processes. Similarly, it is possible to trace the movement of radioactive substances through a plant or the human body and thus learn more about how and where these substances are assimilated. In contrast to radium, most of these artificial radioactive substances have such a short life that no permanent harm is done to the human system.

The present methods of generating electric power are so well established that we are inclined to accept them as permanent. Gradual improvements in present methods have reduced the amount of coal used per kilowatt-hour to approximately one-fourth that required 20 years ago. While this improvement is indicative of real progress in steam power generation, it is still small when compared with the theoretically possible energy that could be gotten from a highly efficient method of energy conversion.

With an increasing knowledge of the fundamental properties of matter and a better understanding of the conduction of electricity in gases, recent calculations and experimental work indicate that it may be possible to use the electromagnetic properties of the rapidly moving ionized products of combustion of certain fuels in conjunction with some suitable electrical transforming device as a means of generating electric energy. A practical development of this idea, which at least appears to be a possibility at the present time, would result in the use of static electrical devices extracting power from the kinetic energy of the gases of combustion without the intervention of rotating electrical machinery.

Although these and many other prospective developments that might be mentioned are indefinite and difficult to evaluate, we can look forward with the expectation that the electrical industry will continue to grow under the stimulation and impetus of new scientific discoveries and advances.

New Indirect Luminaire Improves Drafting-Room Illumination

F. P. KUHL

IN PLANNING the recently completed installation of a new lighting system for the drafting rooms of the Consolidated Edison Company of New York, Inc., the aim was to eliminate glare and obtain 40 to 50 foot-candles of totally indirect light. A study of the fixtures that were commercially available disclosed that approximately eight watts per square foot would be required to obtain the illumination level desired. The heat loss at this rate would have required an air-conditioning system to maintain a reasonable room temperature. The cost of this air-conditioning system would have been at least twice that of the proposed lighting system.

The problem, therefore, resolved itself into developing a fixture that would provide the illumination level desired at a power consumption that would not require an air-conditioning system or a considerable change in the existing conduit and wiring system. In all probability, it is for these reasons that so few existing lighting systems are renovated to meet the standards advocated by the "better light–better sight" campaign.

After a further study of commercially available lighting fixtures, the silvered-bowl lamp was selected as a starting basis. This lamp has a distribution curve that is almost entirely above the horizontal line at the filament center. It also has a self-contained silvered mirror reflector which cannot deteriorate from the collection of dust and which is renewed whenever the lamp is replaced.

Having decided on the lamp and reflector, the next step was to eliminate glare and control the spread of light from the lamp. The lamp was mounted as close to the ceiling as a socket would permit, in order to obtain the shortest path of light, and various combinations of louvers and pans were tested. The final design* resulted in a combination of concentric rings or louvers as shown in figure 1. These rings are made of metal and therefore are entirely opaque, eliminating high brightness on their outer surfaces. The rings and canopy are finished in flat white. The socket husk and spider for supporting the rings are finished in fused aluminum to prevent discoloration from heat.

The concentric-ring combination overcomes the ob-

F. P. KUHL is chief draftsman, Consolidated Edison Company of New York, Inc., New York, N. Y.

* Patent applied for; all rights reserved by the author.

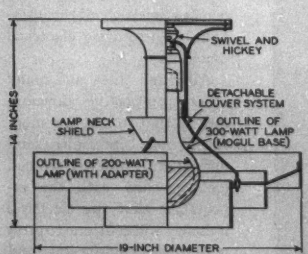
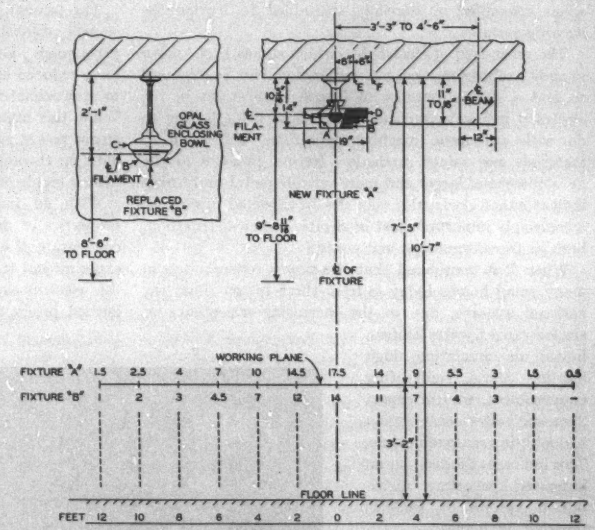


Figure 1. Sectional view of new luminaire


3'-3" TO 4'-6"
2'-1"
OPAL GLASS ENCLOSING BOWL
FILAMENT
REPLACED FIXTURE "B"
8'-6" TO FLOOR
NEW FIXTURE "A"
9'-8 11/16" TO FLOOR
7'-5"
10'-7"
℄ OF FIXTURE
11" TO 18"
℄ BEAM
12"
WORKING PLANE
FIXTURE "A" 1.5 2.5 4 7 10 14.5 17.5 14 9 5.5 3 1.5 0.6
FIXTURE "B" 1 2 3 4.5 7 12 14 11 7 4 3 1 –
3'-2"
FLOOR LINE
FEET 12 10 8 6 4 2 0 2 4 6 8 10 12

Foot-candle readings on working plane, as distributed from one luminaire; values should increase slightly after ceiling is refinished

Brightness Readings; Arrows on Diagram Indicate Position and Angle of View

Location (200-Watt Silver-Bowl Lamp)†	New Indirect Fixture "A" Reflected Brightness		Replaced Semi-Direct Fixture "B" Luminaire Brightness			
			200-Watt Lamp*		150-Watt Lamp*	
	Millilamberts	Candlepower	Millilamberts	Candlepower	Millilamberts	Candlepower
A	126.6	0.26	1,770	3.63	1,280	2.36
B	63.3	0.13	1,480	3.03	1,090	2.24
C	116.9	0.24	1,237	2.54	852	1.75
D	33.1	0.07				
E	564.9	1.16				
F	231.8	0.476				

* Clear Glass † Inside Frosted

Figure 2. Intensity of illumination and surface brightness as measured with the new luminaire (A) and the one it replaced (B)

jection to the reflecting pan of the conventional indirect lighting unit in several ways:

1. Presents a minimum intercepting surface to reflected light from the ceiling.
2. Does not collect dirt and dead insects and, therefore, requires minimum cleaning.
3. Does not present the dark appearance usually found on the under side of indirect lighting reflectors.
4. Provides excellent ventilation for dissipating lamp heat.
5. Lamps can be replaced from floor with lamp changer.

Using 200-watt lamps in the final fixture, an intensity of approximately 38 foot-candles was obtained on a working plane 3 feet 2 inches above the floor at a power consumption of 3.8 watts per square foot. This indicates that 60 per cent of the light flux produced by the lamps reaches the working surfaces of the drafting boards, which is considerably higher than that obtainable from the conventional indirect fixtures. Using 300-watt lamps, nearly 60 foot-candles was realized. These values will increase slightly after the ceiling is refinished. Approximately 7 per cent absorption occurs in the louver system.

During the experiments, a group of draftsmen was subjected to various intensities ranging from 20 to 60 foot-candles while performing normal duties. Each period was of sufficient length to develop a complete reaction. It developed that reflected light from tracing cloth at levels higher than 35 foot-candles was very annoying. The reaction of the draftsmen was most favorable at 30 foot-candles. This level of 30 foot-candles was adopted as the basis of design for the final installation, and is an increase of 150 per cent over the replaced system at an increase in power consumption of slightly less than 60 per cent.

The spacing of the lamps, approximately 6 feet by 9 feet, was governed by the lattice work of the building beams covering the ceiling and by the use of existing out-

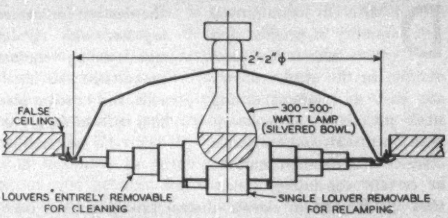
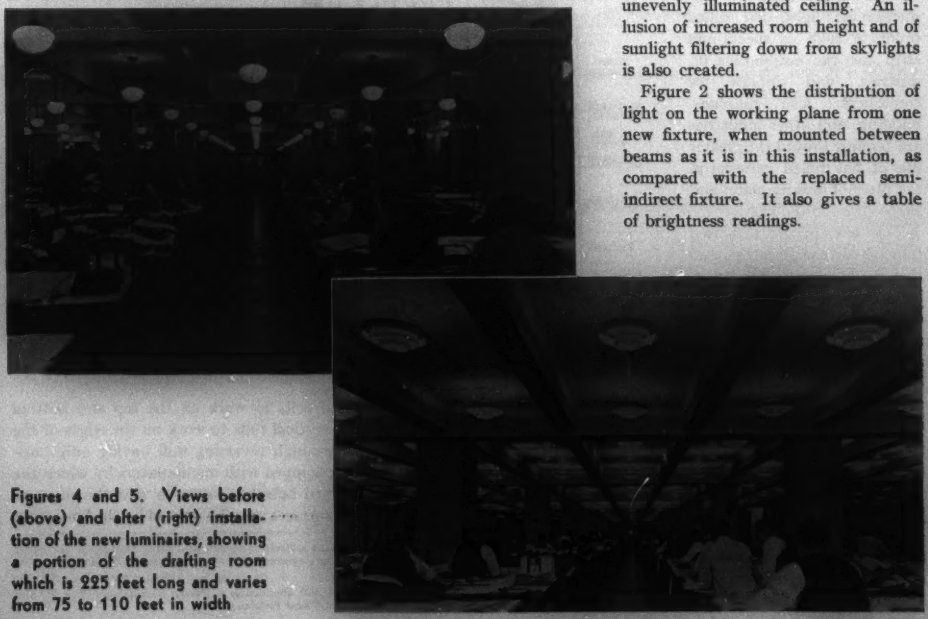


Figure 3. Sectional view of indirect downlight luminaire for flush ceiling mounting, employing the silvered-bowl lamp and concentric-ring arrangement similar to that shown in figure 1. This illustrates the general adaptability of this design principle for other uses

lets, supplemented with additional outlets wherever necessary. Beams are usually an obstacle to indirect lighting installations, flat ceilings being preferred. In this installation effective use was made of the beams to act as curtains, the fixtures being almost concealed when viewed from a distance of three bays or more. The bottoms of these beams have a low surface brightness and present a pleasing pattern on an otherwise brightly but unevenly illuminated ceiling. An illusion of increased room height and of sunlight filtering down from skylights is also created.

Figure 2 shows the distribution of light on the working plane from one new fixture, when mounted between beams as it is in this installation, as compared with the replaced semi-indirect fixture. It also gives a table of brightness readings.



Figures 4 and 5. Views before (above) and after (right) installation of the new luminaires, showing a portion of the drafting room which is 225 feet long and varies from 75 to 110 feet in width

Some Recent Steel-Mill Installations

A. F. KENYON
ASSOCIATE AIEE

The demand for increased amounts of sheet steel, together with revolutionary developments in manufacturing equipment and processes, has necessitated the installation of many new strip mills, and in some plants large blooming or slabbing mills to supply the heavy slabs used as raw material in the strip mills.

DEMANDS for improved quality of product and more economical production in the steel industry are just as insistent during slack periods as at times of peak operation; and even with lessened total demand, markets in certain consuming industries and for certain classes of steel products have been greatly expanded. New construction during recent years, therefore, has been not so much in the primary iron- and steel-producing facilities as in the finish-rolling and processing departments.

A chart (figure 1) showing the distribution of rolled steel products to the various consuming industries for the 16-year period 1922 to 1937 indicates a decline in the production of heavy products such as rails and plates for railroads, structural shapes and plates for the building industry, and large welded and seamless pipe for oil, gas, and water lines. Further indicated is the rise in production of light, flat rolled products such as sheets and strip for the automotive industries, and tinplate for containers; also railroads, building, and other industries are tending toward the greater use of flat rolled material in the place of heavier plates and shapes used in the past.

This demand for increased tonnage of sheets, strip, and tinplate, together with revolutionary developments in equipment and processes for manufacturing these flat rolled products, has necessitated the installation of many new hot and cold strip mills, and in some plants these in turn have necessitated installation of large blooming or slabbing mills to supply the heavy slabs used as raw material in the strip mill.

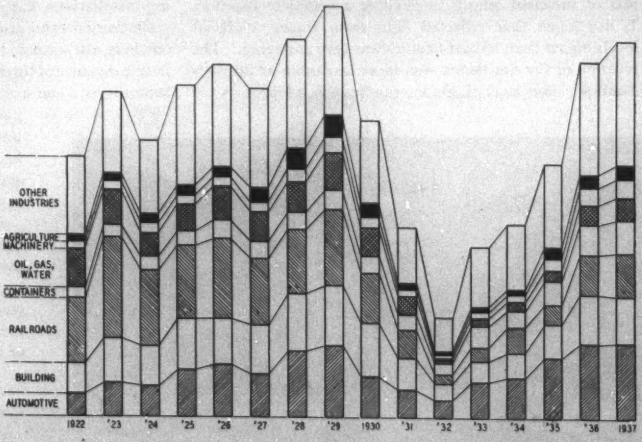


Figure 1. Distribution of steel products to various consuming industries during a 16-year period

Blooming and Slabbing Mills

First step in the production of various rolled steel products is the rolling of ingots, as cast from the open hearth steel furnace, to blooms or slabs suitable for further rolling in finishing mills. Recently installed strip mills produce strip 50, 60, and even up to 94 inches wide, by several hundred feet long. These long, wide strips are rolled from slabs that may be from four to six inches thick, from 50 to 60 inches (and in one mill up to 72 inches) wide, and from 8 to 15 feet long; these slabs may weigh as much as 15,000 pounds. Demand for these extremely large slabs has forced the development of improved blooming and slabbing mills, and during the past five years there have been installed some nine or ten mills primarily intended to produce large slabs for further rolling in wide strip mills.

Wide slabs may be produced by either a universal mill having horizontal rolls to work on the top and bottom of the slab, and vertical rolls to work on the edges of the slab; or by a two-high reversing mill having only horizontal rolls and equipped with manipulators by which the slab may be turned between passes so that the edges as well as the wide surfaces may be worked by the horizontal

Essential substance of an address presented at a joint meeting of the AIEE Toronto Section and the Engineering Institute of Canada, Hamilton, Ontario, April 21, 1939.

A. F. KENYON is steel mill application engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

rolls. Most of the newer mills have been of the latter type.

A recently installed large slabbing-blooming mill illustrates the extreme height and long screws needed for raising the top roll for the edging passes on wide slabs. On this mill the rolls are 43 inches in diameter. The mill rolls ingots of various sizes up to 25 by 66 inches, 25,000 pounds maximum weight, and can produce slabs up to 62 or 64 inches wide. Figure 2 shows the top roll in the raised position. Mill spindles connecting the rolls to the driving pinions are made unusually long—27 feet between joints of the universal couplings—so that the coupling angles will not be excessive when top roll is in that position.

In each passage of the ingot back and forth through the mill, the thickness of the ingot may be reduced by an inch or more, and to make this reduction on a wide ingot requires the driving power of a 7,000-horsepower 700-volt 40/100-rpm d-c reversing motor, which is coupled directly to the mill pinions. The motor will commutate peak currents up to 23,000 amperes, corresponding to maximum torque output of 2,500,000 pound-feet. The armature is 12 feet in diameter and, with shaft, weighs 88 tons. Total weight of the complete motor is over 450,000 pounds. Figure 3 is a general view of the motor room.

The 7,500-kw variable-voltage main-power-supply motor generator set consists of five units: three 2,500-kw 700-volt d-c generators; a 6,000-horsepower 6,600-volt 3-phase 60-cycle 355-rpm wound-rotor induction motor; and a 150,000-pound flywheel, 15 feet in diameter, to equalize the fluctuating power demand of the reversing motor and smooth out the load on the 6,600-volt power system. Peak loads on the reversing motor may reach 15,000 horsepower, but with the equalization provided by the flywheel and automatic liquid slip-regulator control of the induction-motor secondary, the maximum system demand is limited to about 5,500 kw. The mill is capable of a maximum output of about 300 gross tons an hour when it is rolling large slabs.

Rolling wide slabs in a two-high reversing mill imposes severe duty on the screw-down mechanism, because of long screw movements to raise the upper roll before each of the edging passes and to lower the roll after the edging passes. Screw speeds of from 300 to 350 inches per minute are necessary in order to make these movements of 40 or 50 inches in reasonable time, and special lubrication of the screws and driving gears is necessary to avoid excessive wear and maintenance of the mechanical equipment. The electrical driving equipment must have unusual flexibility to assure accuracy in making the small movements between flat slabbing passes, as well as to provide the high speed required for the long movements before and after the edging passes. Almost invariably the screw-down mechanism is driven by two heavy-duty d-c motors, each of about 150-horsepower capacity, and in several cases a special series-parallel controller provides reasonably satisfactory performance. However, on most recent mills, variable-voltage equipment has been selected as affording the greatest smoothness and flexibility of control, together with reduced maintenance of the electrical and mechanical equipment. The slightly higher first cost is more than offset by the improved performance and greater output, and reduction in maintenance. Variable-voltage equipment also has been applied to the front and back main tables, manipulator racks, and slab shears of several mills recently completed. Two variable-voltage motor generator sets (center of figure 3) each consisting of three 150-kw generators, one 250-kw generator,

Figure 2 (below). Delivery side of a 46-inch slabbing-blooming mill

Figure 3 (above). Blooming-mill motor room. The 7,000-horsepower reversing motor may be seen in the background; 7,500-kw flywheel motor generator set in right foreground

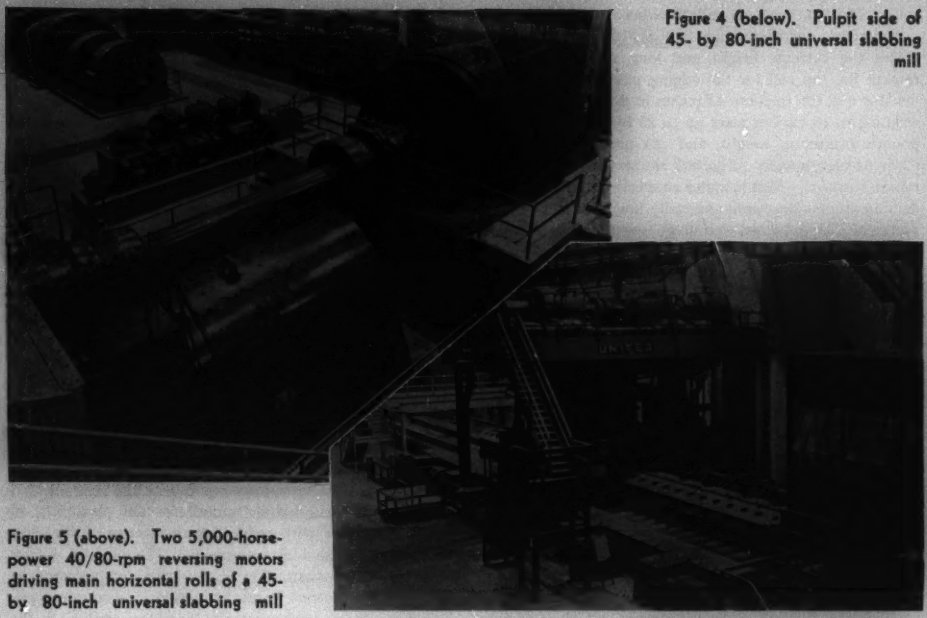


Figure 4 (below). Pulpit side of 45- by 80-inch universal slabbing mill

Figure 5 (above). Two 5,000-horsepower 40/80-rpm reversing motors driving main horizontal rolls of a 45- by 80-inch universal slabbing mill

and a 900-horsepower synchronous driving motor, furnish the variable-voltage power supply to the screw-down table, manipulator rack, and shear motors of the mill described.

Reversing slabbing mills of the universal type, with both main horizontal rolls and auxiliary vertical edging rolls, have some decided advantages because of their ability to work on all four faces of the ingot without having to turn it, but they involve much more complicated and expensive mechanical and electrical equipment and hence are justified only where extremely large outputs of wide slabs are required. Also until recently the arrangement and drive of the vertical rolls limited the edging work that could be done, thus requiring a large number of ingot sizes, and the mill was quite inaccessible, making it difficult and time-consuming to change the vertical rolls or make other adjustments and repairs.

The 45- by 80-inch universal slabbing mill recently installed at a steel plant in the Pittsburgh district overcomes many of the difficulties inherent in earlier mills. Figure 4 shows the pulpit side of the mill, and indicates the arrangement of the drive for the vertical edging rolls. A 3,000-horsepower 60/180-rpm edging-roll motor is located in the mill building on a steel-and-concrete supporting structure about 25 feet high. The motor is coupled to separate spur-and-bevel-gear sets located at the top of the mill housing, and connections to the vertical rolls are by means of specially designed spindles. This arrangement provides much greater strength than earlier designs where the bevel gears were mounted directly on the vertical rolls, enables greater power to be transmitted to the vertical rolls, and also facilitates roll changing. Vertical edging rolls are 36 inches in diameter, and the main horizontal rolls are 45 inches in diameter by 80 inches long. The upper horizontal roll may be lifted 66 inches maximum to facilitate heavy reductions on the first two passes to crack the scale with the ingot on edge, after which the ingot is turned on its side for the remaining flat passes. Ingots range up to 32 by 66 inches, 45,000 pounds in weight, and are rolled into slabs up to 60 inches wide.

Each of the main horizontal rolls is driven separately by a 5,000-horsepower 40/80-rpm 700-volt d-c reversing motor, the two motors comprising a 10,000-horsepower twin-motor drive (figure 5). The 13,000-horsepower combined capacity of the main- and edging-roll motors is the largest power ever applied to a single mill stand. The twin-motor drive for large reversing mills, eliminating the usual pinion stand, was developed by Westinghouse about ten years ago, and two 10,000-horsepower installations were made in 1929 and 1930 for driving a 54-inch blooming mill and 44-inch slabbing mill, both at the South Chicago plant of the Carnegie-Illinois Steel Corporation. Each of the 5,000-horsepower motors for the original drives was built as a double-armature unit, in order to reduce frame diameter and keep the distance between the upper and lower motor shafts to a minimum. In the latest design for the Pittsburgh slabbing-mill drive the 5,000-horsepower rating of each motor is developed in a single unit, which is more efficient than the double-unit machines, and which can be built with only slightly greater distance between the upper and lower motor shafts.

Hot-Strip Mills

Most of the recently installed continuous hot-strip mills have conformed in general arrangement to a fairly well standardized design, and variations have been in details rather than in the general arrangements of the roll stands and principal auxiliaries. The roughing train usually consists of four main mill stands, together with an auxiliary scale-breaking stand preceding the first stand and vertical edging mills proceding each of the other three roughing stands. The finishing train consists of six main mill stands, together with one auxiliary scale-breaking stand. In the roughing train the steel slab or bar is relatively short and the stands are spaced well apart, so that the bar is in only one main stand at one time, and these stands therefore can be driven by constant-speed a-c induction or synchronous motors. In the finishing train the bar has been greatly elongated, and the stands are spaced as closely as possible, so that the bar may be in several or all of the finishing stands at one time. These stands therefore must be driven by d-c adjustable-speed motors to be able to match the relative speeds properly, and to avoid looping or stretching the strip between stands. Figure 6 is a view of a typical continuous hot-strip mill, showing the closely spaced finishing stands in the foreground and the roughing stands and slab-reheating furnaces in the background. The motor room of a modern 56-inch mill is shown from the finishing end in figure 7. Finishing stands are driven by six 3,000-horsepower d-c adjustable-speed motors operating at 600 volts. Power is supplied to them by two 6,000-kw motor generator sets shown along the left wall in the illustration.

Large 80- to 98-inch mills have main drive motors totaling from 40,000 to 43,000 horsepower.

Earlier hot-strip mills were arranged to handle only comparatively short slabs, and the roughing stands were geared to operate at quite high rolling speeds, so that the duration of the roughing passes was only a few seconds and the peak loads were very high as compared with the average load. Under such conditions these roughing stands were equipped with flywheels to equalize the peak loads and were most satisfactorily driven by wound-rotor induction motors. In more recent mills the rolling speeds of stands 1, 2, and 3 usually are much slower; also the trend is toward the rolling of longer slabs in order to secure as long a strip as possible in one piece. Thus the duration of the roughing passes now may be 15 seconds or longer, and the peak loads are reduced because of the slower rolling speed. Flywheels are of little value where the load persists for more than six or eight seconds, and synchronous motors, therefore, may be successfully applied. One 56-inch and one 44-inch mill each have all four roughing stands driven by synchronous motors, and synchronous motors also have been applied successfully to one or more of the roughing stands of several 56-, 66-, 77-, and 80-inch mills. Synchronous motors have advantages of higher efficiency and lower first cost, and by proper control they may be used for power factor and voltage control.

The d-c finishing-stand and scale-breaker motors on a large hot-strip mill may total 25,000 horsepower and be supplied from generators totaling 18,000 kw, this entire capacity being concentrated on a 600-volt d-c bus not much longer than 100 feet. In the event of a failure at any point in this compact system, the short-circuit current easily may be 250,000 amperes or more, and special air circuit breakers and bus arrangements have had to be developed to withstand stresses developed during such abnormal current flow. Figure 8 shows a 6,000-ampere 750-volt single-pole heavy-duty air circuit breaker of the type developed for this service. Main and arcing contacts are arranged so that flow of current through the breaker tends to increase the contact pressure and thus prevent burning of the contacts before the breaker is unlatched. Extremely rapid opening is secured by means of heavy springs and the blowout effect of the current flow; the shock of opening is absorbed by a combination of pneumatic and rubber bumpers. The various parts are assembled on two rigid insulated steel posts. Normally the breaker is of the pedestal type for floor mounting, although it can be arranged for panel mounting when necessary.

A composite section across the finishing end of the motor room for a 56-inch strip mill installed during 1939 is shown in figure 9, which indicates relative locations of power-supply generators, finishing-mill motors, circuit breakers, and busses. The motor room is only 60 feet,

Figure 6. A 76-inch continuous hot-strip mill

4 inches wide, restricting the space between the motor and motor generator foundations for the finishing-mill d-c control equipment to about 13 feet, 3 inches. Main busses, therefore, are located inside the foundations underneath the motors and motor generator sets, in order to place the air circuit breakers closer to foundation walls and provide adequate passageway between breakers. This arrangement also gives greater accessibility to the motor dynamic-braking control panels, generator-field and master-control panels, and motor-operated rheostats, which are mounted along the foundation walls between the main circuit breakers.

Figure 7. View of the motor room of a modern 56-inch continuous hot-strip mill from the finishing end

Operation of the many large electrical machines in a relatively small motor room results in large heat losses, necessitating circulation of extremely large volumes of ventilating air to dissipate the losses and keep the machines and motor room at reasonable temperature. In some instances filtered air is blown up through the machines and into the motor room from which it is discharged through roof ventilators or other openings. However, air filters require a great deal of maintenance and are only partially effective in removing dirt, so that much dirt is blown into the machines. The air is not cooled, and in warm weather the motor room may become uncomfortably warm for attendants. Many recent installations, therefore, have provided for cooling and recirculation of ventilating air, reducing the quantity of dirt carried into the machines, and maintaining more reasonable temperatures. In one 56-inch continuous hot-strip mill the machines are arranged with suitable enclosing covers so that the warm air from the machine is not thrown out into the room but is collected and discharged downward into the foundation pits. Warm air passes through the air coolers, which absorb heat and cool the air to a reasonable temperature, usually about 85 to 90 degrees Fahrenheit; then recirculating fans return the cooled air to the motor room where it again is drawn into the machines. A small makeup filter and fan are provided to compensate for leaks from the closed recirculating system and to keep the motor room under slight pressure so that external dirt will not sift in. In this particular mill each of the four air-recirculating fans is rated at 80,000 cubic feet per minute at a three-inch discharge pressure, requiring a 75-horsepower driving motor. Each of the four coolers is designed to absorb a 600-kw loss and to cool the air to 90 degrees Fahrenheit; each requires about 400 gallons per minute of cooling water at 75 degrees Fahrenheit. The air-makeup fan is rated at 25,000 cubic feet per minute. Additional coolers and recirculating fans are provided for the roughing-mill motors and auxiliary motor generator sets, and a second makeup filter and fan are provided at the roughing end of the motor room.

Figure 8. Heavy-duty 6,000-ampere pedestal-mounted air circuit breaker

Cold-Strip Mills

The hot-strip mill ordinarily produces strip ranging from 0.050 to 0.125 inch thick. A part of this hot-mill output may be sold as hot-rolled strip or sheets, and in plants with older finishing mills the hot strip may be cut and further reduced to the required final gauge by hot rolling in sheet or tinplate mills. However in most modern installations the hot-strip mill is paralleled by cold-reduction strip mills, and a large proportion of the hot strip is cold reduced to the finished thickness. Cold-reduced strip for tinplate was first produced about ten years ago, and at present cold-reduction mills provide more than 55 per cent of the total tinplate capacity of United States plants.

Cold-strip mills may be classified as to type of mill, whether single-stand reversing or multistand tandem, and as to class of product, whether for wide, relatively heavy-

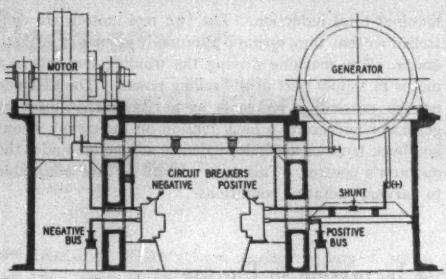


Figure 9. Arrangement of air circuit breakers and main busses for strip-finishing control

gauge sheets as required for automobile bodies and fenders, metal furniture, and refrigerator cabinets, or light-gauge narrow strip for tinplate.

Ordinary automobile sheets range from about 0.030 to 0.050 inch thick, and up to 80 inches wide, and in usual practice may be cold rolled in about three passes from hot strip 0.080 to 0.125 inch thick. Strip for tinplate is 0.008 to 0.012 inch thick, 24 to 36 inches wide, and in usual practice requires about five cold-reduction passes to roll from hot strip 0.060 to 0.080 inch thick. Mills for tinplate therefore are relatively narrow—usually 42 inches—have four or five stands if they are of the tandem type, and run at speeds of 1,500 feet per minute or faster in order to provide the required output capacity of the light finished material. Mills producing sheet material may range up to 98 inches wide, consist of only three stands, and usually run at speeds of from 500 to 600 feet per minute.

A typical five-stand tandem cold-reduction 42-inch strip mill (figure 10) used for rolling light-gauge strip for tinplate, has stands spaced on 13-foot centers, with tension winding reel following the last stand. This mill and a second duplicate mill in the same plant were originally built to operate at a maximum rolling speed of 1,200 feet per minute, but have been changed to permit operation up to 1,500 feet per minute. On favorable schedules outputs of 40 net tons per hour are attained, and the two mills together can produce 30,000 tons or more per month. The main-drive electrical equipment (figure 11) has a 500-horsepower 600-volt d-c motor driving stand 1 and four 1,250-horsepower motors driving stands 2, 3, 4, and 5. The 250-horsepower winding reel is located in the mill building. Variable-voltage power for the mill and reel motors is supplied by a 5,000-kw synchronous motor generator set.

The largest mill yet installed is a 98-inch three-stand tandem mill (figure 12) capable of rolling strip up to 94 inches wide, such as required for automobile bodies and fenders and refrigerator cabinets. The mill is geared for a maximum rolling speed of 800 feet per minute. The number 1 mill is driven by a 1,500-horsepower 300/600-rpm 600-volt d-c motor; numbers 2 and 3 mill motors are each rated at 2,500 horsepower, 225/450 rpm; and the winding-reel motor 600 horsepower, 250/875 rpm. Variable-voltage power is supplied by a 6,000-kw synchronous motor generator set. The motors are located in the mill building without a protecting motor room, and are completely enclosed and ventilated by an air-cooling and recirculating ventilation system installed in the basement control room under the motors.

Tandem mills as just described have large production capacity, but require large capital investment and in some respects are not as flexible as single-stand reversible mills.

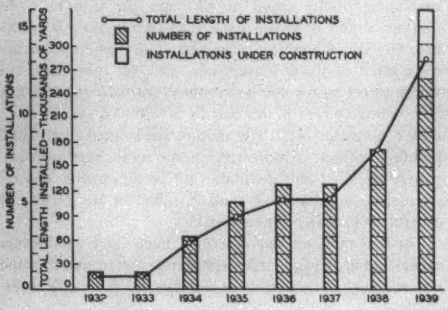
Figure 11 (below). Motor room of a 42-inch tandem cold mill

Figure 10 (above). A 42-inch five-stand tandem cold-reduction strip mill for tinplate

A reversible mill consists of a single mill stand with a tension reel on each side of the mill stand. Mill and reel drives are reversible so that the strip may be unwound from one reel, passed between the reducing rolls, and rewound on the second reel. The mill rolls then are screwed down and the operation reversed so that the strip is unwound from the second reel, passed back through the mill, and rewound on the first reel. This reversible process is continued for as many passes as are required to effect the required total reduction. The two reel motors are controlled so that they operate alternately as motor or generator. The machine driving the winding reel acts as a motor to supply part of the rolling power. The machine on the unwinding reel acts as a regenerative braking generator and exerts a back tension on the strip. Front and back tensions are independently adjustable under the operator's control. This type of mill is thus adaptable to varying operating conditions.

Use of Pressure-Type Cable Increasing in Europe

AMERICAN engineers undoubtedly will be interested in some of the latest data and statistics on the use of a form of extra-high-voltage cable that has not yet been employed in America, namely, the pressure cable, which has been used in Europe since 1932 in increasing amounts.



The main problem in high-voltage paper-insulated cable is the prevention of voids during contraction cycles when load is reduced. In an oil-filled cable, voids are prevented by the flow of oil from reservoirs into the cable while it is cooling, through channels in the cable itself. In the pressure cable, the same result is accomplished by gas pressure external to the lead sheath. To assist the lead in undergoing this slight diaphragm action, the sheath is made either slightly triangular or oval in shape and reinforced with a bronze tape to prevent cumulative bending. In the original form as described by Hochstadter, Vogel, and Bowden in *Elektrotechnische Zeitschrift* in 1932, page 145, the cable is placed in a steel pipe filled with nitrogen under a pressure of about 15 atmospheres. The cable itself is either a three-conductor cable with a triangular sheath, or a three-conductor *SL* (separately leaded) cable with individual elliptical sheaths. In the latest developments in England, a reinforced lead sheath has been substituted for the steel pipe as a pressure restraining medium, this type being known as the self-contained pressure cable. The latter type was described by K. S. Wyatt (A'32) at the Conférence Internationale des Grands Réseaux Électriques á Haute Tension, Paris, 1939.

The accompanying tabulation shows the installations in service or under construction. Of these all are of the pipe type with the exception of the last two which are self-contained. The accompanying graph shows the growth in mileage of this type of pressure cable.

Installations of Pressure-Type (Hochstadter) Cable

Pipe-Line and Self-Contained Types; Total Length About 288,000 Feet

No.	Location	Kilovolts	Conductors: Number	Conductors: Cross Section (Circular Mils)	Conductors: Material	Insulation Thickness (Mils)	External Diameter of Cable (Inches)	Internal Diameter of Pipe (Inches)	Circuit Length (Feet)	Year Installed	Load (Kva)	Type of Construction
1	London, England	66	3	191,000	Copper	340	2.97	4.76	13,110	1932	31,500	Pipe line
2	Muldenstein, Germany	60	2	237,000	Copper	315	2.96	3.54	1,281	1934	22,000	Pipe line
3	Copenhagen, Denmark	55	3	187,000	Copper	236	2.68	3.15	43,200	1934	28,000	Pipe line
4	Oslo, Norway	66	3	295,000	Copper	276	3.27	3.94	10,320	1935	45,000	Pipe line
5	Stettin, Germany	110	3	237,000	Copper	473	4.1	4.93	24,810	1935	60,000	Pipe line
6	Braunschweig, Germany	50	3	295,000	Aluminum	236	2.84	3.54	17,550	1936	28,000	Pipe line
7	Barmen, Germany	50	3	237,000	Aluminum	236	2.84	3.54	56,400	1938	25,000	Pipe line
8	Elberfeld, Germany	50	3	295,000	Aluminum	236	3.07	3.54	5,340	1938–39	27,000	Pipe line
9	Elberfeld, Germany	50	3	295,000	Aluminum	236	3.07	3.54	9,180	1939	27,000	Pipe line
10	Elberfeld, Germany	50	3	187,000	Copper	236	2.72	3.15	13,710	1939	27,000	Pipe line
11	Munchen, Germany	100	2	474,000	Aluminum	473	4.21	4.93	17,700	Being installed	36,000	Pipe line
12	Watenstett, Germany	120	3	365,000	Aluminum	551	4.6	5.91	9,030		60,000	Pipe line
13	Magdeburg, Germany	60	3	474,000	Aluminum	276	3.52	3.94	27,600	Being manufactured	40,500	Pipe line
14	Braunschweig, No. 2	60	3	257,000	Aluminum	276	2.99	3.54	19,650		32,000	Pipe line
15	London, No. 2	66	3	191,000	Copper	285 Min.	3.67		13,110		32,000	Self-contained
16	Ferrybridge, England	66	3 Single Cores	636,000	Copper	285 Min.	2.75 Approx.		450		60,000	Self-contained

Electricity in Chemical Plants

KENNARD PINDER
MEMBER AIEE

Because many chemical plants require heat for process use, many opportunities exist for the development of combined heat and electric-power supply systems in these plants, which are among the largest industrial users of electricity. Special precautions must be observed in selecting electrical equipment for use in chemical plants, because of the prevalence of flammable or corrosive fumes.

CHEMICAL PLANTS are among the largest industrial users of electric power and electric-power equipment today. Two of the chief engineering and economic problems arising in connection with the building of chemical plants are the layout of the power system and the selection of drives for the various pieces of apparatus. These factors are frequently primary considerations in determining the general location of chemical plants.

Chemical plants may be divided into two general classes regarding the electric-power supply:

1. Those in which the processes are dependent essentially upon electric supply.
2. Those in which the processes are dependent chiefly upon steam.

To the first class belong the electrochemical or electrometallurgical plants which carry on some electrolytic process, or else some heat reducing process only possible or commercially feasible at the high temperatures obtainable by electric heat, and which at the same time have few operations requiring low-temperature heat. This class of plant depends primarily upon low-price electric power and therefore is restricted to localities where power may be generated cheaply, such as near the coal fields or some large hydroelectric development.

To the second class belong the chemical plants that carry on some process in which the solution of chemicals or the evaporation of excess moisture requires relatively low temperatures such as may be obtained from steam. This class of plants is located with relation to raw materials, markets, labor, transportation facilities, supplies of fuel, and intermediate products. The cost of electric power, either generated or purchased is of secondary importance. Plants of this type are not confined to certain localities, but are distributed throughout the country; however, for other reasons they are somewhat concentrated in the eastern section of the United States.

Practically all modern chemical equipment in the second class of plants must be driven and is, therefore, power consuming. Electric power and steam heat frequently go hand in hand in many industrial processes. A list of the processes requiring electric power and heat and the interrelation of processes for various industries is given in table I.

Relation of Steam Heat and Electric Power

Steam is of essential value in the process industry. Amount, pressure, and temperature of steam used vary widely even among the same processes carried on by different manufacturers. In general, so far as the low-temperature heating operations are concerned, steam is the most economical medium to employ. In plants that require process steam in large and fairly constant quantities, many opportunities exist for the development of inexpensive power services.

Through the use of high-pressure boilers and pressure-reducing prime movers, the process steam required may be obtained, either as bled steam or high-pressure exhaust steam, while at the same time considerable quantities of electric energy can be produced very cheaply—sometimes for as low as two mills per kilowatt. A most interesting problem develops in the process industry by permitting the extraction of steam for electric-power generation from the steam generated by high-pressure superheating boilers before the steam is turned over at process pressure to the chemical processes. In the past, there was a tendency to treat the problems of an industrial power plant the same as those of a public-utility plant. Both have much in common, but because the industrial power plant must be necessarily considerably smaller than a public-utility plant and, therefore, less efficient, it is amiss to assume that purchased power will be cheaper. This might be true if the supply of power did not have connected with it the supply of heat. The supply of steam and electric power to a process is not two problems, but a combined single problem. The efficiencies of a public-utility power plant and an industrial power plant cannot be compared as a guide in determining which source will be most economical. The true criterion of a power plant's performance is the amount of heat put to useful work, or, in other words, the amount of preventable waste that can and should be avoided.

It is the primary business of public-utilities to sell power and services. It behooves them to render the best possible service without interruptions at the lowest possible costs within economic reason. The problems of an industrial power plant of the kind here being discussed are peculiar. The "by-product" power is incidental to furnishing heat. "By-product" power from pressure differences is in no way related to power from waste fuel, from the waste heat of process combustion, or from waste exhaust steam condensed through turbines. It is limited to that power which an industry can produce by generating steam at pressures within present ranges of practice and

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KENNARD PINDER is electrical engineer, E. I. du Pont de Nemours and Company, Inc., Wilmington, Del.

Table I. Interrelation of Processes in Chemical Plants

Process Industries	Absorption	Agitating & Mixing	Centrifuging	Chemical Processes	Crushing & Grinding	Dissolving & Leaching	Distillation	Drying	Dust & Fume Handling	Evaporation	Extraction	Filtration	Gas & Air Handling	Heat Technology	Liquid Transferring	Material Handling	Pressing—Hydraulic	Refrigerating	Sifting & Screening	Solvent Recovery	Thickening	Weighing
	Unit Processes																					
Cement & Lime		●		●	●			●	●			●	●	●	●	●			●		●	●
Ceramics & Glass		●		●	●			●	●			●	●	●	●	●	●		●		●	●
Chemicals	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Coal Products	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Electrochemical Products	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Explosives—Cellulose	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Fertilizers		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Glue & Gelatine		●		●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	●
Leather Tanning		●		●	●	●	●	●		●			●	●	●	●	●	●	●		●	●
Paint & Varnish	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Petroleum Refining	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Pulp & Paper	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Rayon-Cellulose & Acetate	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Rubber	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Soap		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Sugar Refining		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●		●	●

then passing this steam through a turbine or engine and exhausting it at a pressure high enough to supply a definite process requirement for heat deliverable as steam. The power plant of a process industry is more of a heating plant than a power plant; the problems are heat-engineering problems rather than power problems. It is only necessary to determine what degree of perfection is warranted to secure the best possible economy for one industrial plant, rather than for a group of industries as the central station must necessarily supply. The balancing of the quality of power service against its cost is of fundamental importance in the process industries. These are the greatest differences between an industrial power plant and a power plant, the single purpose of which is to produce power. A misunderstanding of the heat-power problem is a barrier to potential savings.

Wherein does the economy of "by-product" power generation lie? It is not difficult to prove that, in general, "by-product" is the cheapest power available to an industrial plant, providing operating conditions requiring electric power and steam heat are favorably balanced. In the typical steam plant there are three general steps:

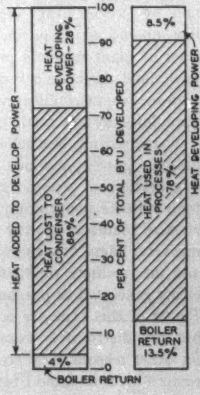
1. Heat stored in fuel is delivered to a plant.

2. The fuel is burned and the stored heat is liberated and transferred to water and steam in the boilers.

3. The accumulation of heat in the boilers is transferred into electric power by a turbogenerator or an engine-generator set, or it is carried by the water and steam to the various processes.

If there were no waste of heat and the boilers, turbines, and generators were 100 per cent efficient, a quantity of fuel containing 3,412 Btu could generate one kilowatt-hour. It is impossible, however, to transform all of a given amount of heat supplied to a working substance into work. Modern boiler units operate at efficiencies of 80 to 85 per cent, the latter figure not being unusual; turbines operate at 95 to 98 per cent efficiency; and generators, 90 to 96 per cent. With these efficiencies, it is possible to produce one kilowatt-hour of "by-product" power at a fuel consumption rate equivalent to 4,300 to 5,000 Btu per kilowatt-hour, or 0.3 to 0.4 pound of average coal. The heat that cannot be transformed into work and

Throttle steam for both condensing-turbine and by-product generation is at 400 pounds gauge pressure and 200 degrees Fahrenheit superheat. Condenser turbine exhausts to a 29-inch vacuum. "By-product" generation exhausts at 80 pounds back pressure and 60 degrees Fahrenheit superheat. If the heat content of one pound of throttle steam is 1,330 Btu, the mechanical efficiency 97 per cent, the electrical efficiency 96 per cent, and all items are the same for each turbine, then the following is a comparison of the two systems:



Condensing Plant

$$\text{Pounds steam per kilowatt-hour at turbine throttle} = \frac{3{,}412}{0.28 \times 0.97 \times 0.96 \times 1{,}330} = 9.8$$

$$\text{Btu per kilowatt-hour at turbine throttle} = 9.8[1{,}330(0.28 + 0.68)] = 12{,}800$$

"By-Product" Plant

$$\text{Pounds steam per kilowatt-hour at turbine throttle} = \frac{3{,}412}{0.085 \times 0.97 \times 0.96 \times 1{,}330} = 32.8$$

$$\text{Btu per kilowatt-hour at turbine throttle} = 32.8 \times 0.084 \times 1{,}330 = 3{,}660$$

Figure 1. Proportion of heat used in condenser-turbine (left) and "by-product" (right) power generation

that must be rejected by the turbine can be used in the processes. In the central-station plant, the heat exhausted from the turbine is practically useless because of its low temperature and lack of pressure; such a condensing plant, even when operating at 1,400 pounds steam pressure and employing both the generative and reheat cycles must have a fuel consumption equivalent to 11,000 to 14,000 Btu per kilowatt-hour, or 0.8 to 1.0 pound of average coal.

In the "by-product" power plant, the heat may be extracted from a noncondensing unit at any desired pressure and temperature (this, of course, depends upon the initial pressure and temperature) and put to practical uses in the process. Temperature difference is necessary for heat transfer, and pressure difference is necessary for steam velocity in the unloading stages of the turbine to the processes. For this reason, considerably less power will be produced in the "by-product" plant than in the central station for the same fuel consumption, but the proportion of heat usefully applied in "by-product" generation to central-station generation is about in the ratio of three to one. "By-product" energy need be charged only for the heat actually used in passing through the turbine. This is not true for a central station because in a condensing steam turbine the heat of vaporization of the steam at the exhaust pressure is an unusable end-product that must be carried away by the condenser circulating water.

In the matter of selecting turbines for a plant, no general statement can be made because the conditions of every problem are different. However, in general, the following is correct:

1. Where the electrical load is predominant, the turbine should be a condensing-extraction type.

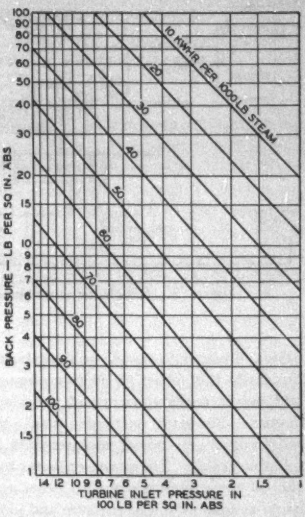
2. Where the steam load is predominant, the turbine should be a noncondensing-extraction type.

3. Where the steam demand balances the electrical demand, the turbine should be a straight noncondensing type. This type is seldom used because the balanced conditions are seldom obtained; however, the noncondensing turbine may be used in conjunction with a condensing turbine, and the steam may then be bled off the noncondensing turbine at process pressure. If the quantity of steam bled off is not all required for the process, it may be passed through the lower stages of the condensing turbine and used to produce power.

Figure 1 shows the magnitude of the heat quantities in the steam cycle of a condensing plant and of a "by-product" plant. As shown in the figure, a larger quantity of steam is required to develop a kilowatt-hour with "by-product" generation, but the heat energy (Btu) chargeable to power is considerably less than that required by condensing-turbine generation. The percentages given are for a specific problem, but indicate relative proportions of uses of the generated steam.

Figure 2 gives the power available from steam-process reductions for process use at various turbine inlet pressures and various extraction pressures. This chart is valuable for making preliminary estimates of power possibilities.

There are many schemes of connecting equipment and apparatus for the generation of by-product power from steam used later for process and heating. Figure 3 shows an arrangement of a turbine expanding some steam from



Graph is laid out for 100-per cent turbine efficiency so that conversion may be direct for substantial quantities. Actual yield in power may be taken at 70 per cent of that for the ranges plotted. Pressures are shown in pounds absolute (14.7 pounds higher than plus gauge pressures). Following vertically from any generated pressure and horizontally from any exhaust or process pressure, the axis will intersect at a value indicating the kilowatt-hours that would be produced by passing 1,000 pounds of steam from the generated pressure to the pressure used in the process. These values are plotted for a fixed superheat of 150 degrees Fahrenheit above the temperature at the generated pressure. Superheat variation has a very marked effect on the available power. The graph, however, is useful for preliminary estimates of power possibilities, as the curves permit approximation from figures on steam-pressure drop

Example: Dissimilarity of conditions will produce identical yields in power per unit weight of steam passed. On the curve for 40 kilowatt-hours per 1,000 pounds, note that this power will be produced by from 375 pounds to absolute, and also the same production is possible from passing from 1,200 pounds to 55 pounds. "By-product" power from pressure differences is practical only when the differences are effectively great as shown by the curves, and when the quantities of steam are substantial and continuously used

Figure 2. Power available from steam-process reductions for process use

boiler pressure to a process bleed point and the remainder passing through the lower stages of the turbine to the condenser. Figure 4 shows an arrangement using high-pressure boilers which supply two high-pressure turbines; one high-pressure turbine exhausts to a low-pressure condensing turbine and the second to an evaporator supplying the process steam.

Commercial development of high-pressure steam (1,000 pounds and above) has opened a field of unlimited possibilities in the direct application to chemical processes, but possibly greater possibilities in the field of power generation from steam later bled off or exhausted for process use at moderate pressures.

An approach to the application of steam for both by-product generation and process use would be for the chemical engineers, who are familiar with the process requirements, to set the process pressure or pressures as low as possible for economical production and compile daily load curves for process steam and power demand. In the

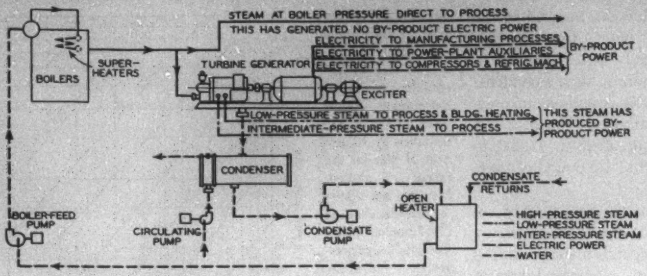


Figure 3. Schematic arrangement of "by-product" power supply

design of plants to supply process steam and power simultaneously this factor of relative amounts of process heat and power required is one of considerable economic influence. For each particular plant, this ratio of steam requirements to power requirements has certain determinable limits. The power engineer by proper consideration of these limitations with other economic conditions could assume an initial pressure and plot from the process-demand curve, a curve of the by-product power available. The latter curve then could be compared with the power requirements and if found insufficient at all hours during the day the boiler pressure may be increased, or the temperature of the steam generated may be increased without a change in pressure, or both the temperature and pressure of the turbine-throttle steam may be changed, until the electric power made available by by-product generation would balance that needed. The most effective way of all to increase the power output is to decrease the exhaust pressure.

In actual practice, it may be more economical not to carry the pressure to a point where all the power required can be generated as a by-product of process steam. The propinquity of a central station and a connection with a utility system is a good thing as a stand-by and to take peak loads in excess of power generated. Unfortunately, utility companies by their demand charges under stand-by conditions tend to make such connections unprofitable.

If power is purchased, the demand charge may range from 20 per cent to as high as 75 per cent of the amount of the power bill. The sum total of all the current demands of the processes constitutes the maximum demand on the electric company's power plant. But, of course, all these maximum demands never will occur at the same time, so the load factor, or ratio of actual consumption to maximum demand is only a part of the maximum demand that the power house must be prepared to meet.

Figure 5 shows a load curve for a plant having peak demands. The average load is much smaller than the maximum demand; the load factor is low and the power company, in order to make a profit on their business, must charge a high rate for the low load factor.

Figure 6 shows a load curve for a plant having an even demand. The load runs fairly even and the average load and maximum demand are nearly equal, resulting in a high load factor. The cost per unit for current would be lower for the same total kilowatt-hours than in the first plant.

Knowledge of what maximum demand and load factor means can be applied so that money may be saved on the power bill through the reduction of maximum demands. The heavy power-consuming processes should be scheduled so that the peaks for the various processes would not occur at the same time, and by overlapping the operating periods the maximum demands would be reduced. Reduction of the maximum demand will result in a reduction of power cost for the same power consumption.

Selection of Electrical Equipment

Rarely are electric motors subjected to more severe services than under the dusty, corrosive conditions found in most chemical plants. As regards the selection of motors and motor-control equipment, the chemical industry may be divided into three groups involving:

1. Fire or explosion hazards.
2. Heat-damage hazards from high temperatures.
3. Corrosion hazards from acid and alkali fumes and from vapors and excessive moisture.

Fire and explosion hazards are encountered in the handling of materials in certain chemical-engineering industries. Electrical equipment and static electricity are the

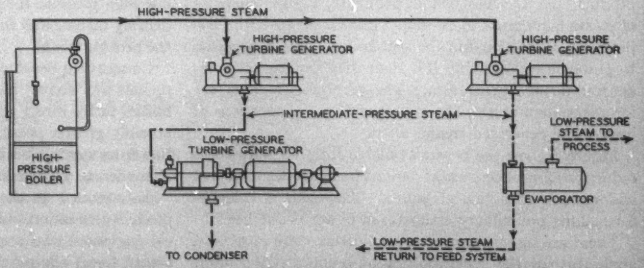


Figure 4. Schematic arrangement of "by-product" power supply using high-pressure boilers and turbines

usual sources of such hazards. Static electricity of high voltage can be generated by transmission belting and may ignite chemical fumes. Static charges may be built up in one or all of three ways: by the separation of the belt from the pulley, the friction of the belt on the pulley, and the friction of the atmosphere on the belt. The principal source of static charge is the separation of belt from the pulley. Charges are generated on both the pulley and the belt under certain conditions. Whenever two dissimilar materials that have been in contact are separated, a static charge results.

Motors, pulleys, and shafting can be grounded, but the belt, usually a nonconductor, allows the potential to build up under some circumstances until sparking occurs; this is sometimes the cause of mysterious fires and explosions occurring in the handling of volatile solvents. An effective means for the prevention of static on belts is as follows: A wooden frame supported from the ceiling or overhead

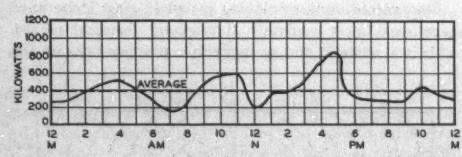


Figure 5. Load curve for plant having uneven demand

Averge load is much less than maximum demand; hence load factor for this plant is low

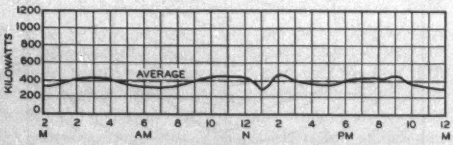


Figure 6. Load curve for plant having even demand

Average load and maximum demand are nearly the same; hence load factor for this plant is high

beam has attached to it a piece, or pieces, of ordinary copper screen wire that is held in contact with the moving belt and grounded by means of copper wires connecting with the sprinkler system or water main. The screen wire is sufficiently flexible to maintain a continuous contact with the belt without exerting a pressure that would cause excessive wear.

As the result of recent investigations by some prominent manufacturers, it has been found that charges on the driving belts can be dissipated by treating the belts with an aqueous dispersion of colloidal graphite. This electric furnace product is a good conductor of electricity, and the graphite films formed in the belts carry static charges from the pulleys to the frames of the machines.

The dangers of static electricity from belting in the presence of flammable vapors and also the inability of this medium of transmission to give the required accuracy of speed with certain types of apparatus has brought about the development of such power transmission methods as the reduction gear units directly connected to the motors.

The majority of industrial chemical equipment is operated under what is known as the "closed system," but regardless of this precaution flammable and explosive vapors are at times present in the areas surrounding and adjacent to the apparatus. The motors and control equipment should also be operated as a closed system. The motors driving the equipment may be placed in a sealed space or in an adjacent room. If they are located in the same area as the equipment, they should be of the totally enclosed fan-cooled type for fire-hazardous locations and of the explosion-tested type for certain explosion-hazardous locations. It has been found practically impossible to keep vapor, fumes, and some corrosive dusts out of dustproof control equipment, but immersing the control equipment in oil has given very satisfactory results.

If the ambient temperature is high, say above 40 degrees centigrade, motors having a 40-degree rise should be selected or ordinary motors derated about 20 per cent in output. If the ambient temperature is above 50 degrees centigrade, it might prove advisable to install pipe-ventilated motors drawing the cooling air from the outside.

For corrosive, hazardous locations, the equipment should be the same as for the "closed system" of operation. In addition the equipment should be protected with an acid- and alkali-resisting paint.

Synchronous motors can be used to good advantage in driving equipment for refrigeration and compressed-air service. This type of motor offers some power-factor correction. In the smaller industrial plants, when the auxiliary electric power is an appreciable part of the total generator capacity, it is very desirable to have the power-factor-correction capacity. Such a type should always be used if possible when power is purchased from a public utility, as it means lower monthly billings.

Distribution System

The distribution system may be either aerial or underground. The aerial method is very much the cheaper where distances are in the order of 1,000 feet or more, but should never be considered where the industrial site is congested. If overhead, the usual method of distribution is by means of triple-braid weatherproof conductors on wooden poles or steel towers. If underground, then varnished-cambric lead-covered, or other suitable insulated, cables are used in fiber ducts encased in a concrete envelope.

If the industrial load is small, say less than 500 kva, and the distances of distribution not greater than 1,000 feet, the generated voltage can be 220 or 440 volts. On larger projects, it is preferable to generate at 2,300 volts or higher and the energy at this voltage is transmitted to small local outdoor or indoor substations and then further distributed at 220, 440, or 550 volts to the industrial loads; 2,300-volt motors may be supplied from the 2,300-volt bus in the substation by means of local switching. The higher voltage requires the use of oil circuit breakers at all points, while the lower voltage permits the use of carbon

breakers or safety switches in the power house and substations, and safety switches in the industrial buildings. The substations should be located as close to the center of distribution as possible.

Metering

A minor but nevertheless important item in the supply of power services to the various processes or departments is that of metering. The power requirement for each department, building, process, or section of the manufacturing plant, together with the total for each service from its point of origin, should be metered. The sum of the individual loads should be balanced daily against the total generated output and any discrepancy corrected immediately. Any losses noted may be found more easily, increases in consumption by any division noted and explained, and controversies over service charges backed up with documentary evidence of actual consumption. Thus meters of the recording type are a worth-while investment because of their aid in detecting losses from the distribution system and in allocating equitably service costs for accounting purposes. The meter usually used for this purpose on feeder circuits is the kilowatt-hour meter. An ammeter for each circuit and a voltmeter for a group of circuits may be used in determining the power factor of the load. The feeder circuit and also the generator capacity are dependent on the ampere requirements and not upon the kilowatt load.

Artificial Illumination

As regards artificial illumination, the chemical industry may be divided, just the same as with electric control equipment, into several groups involving:

1. Explosive material, fumes, or vapor.
2. Alkali fumes and vapors.
3. Acid fumes and vapors.
4. Excessive moisture.
5. Laboratory.
6. Yards.

The processes are usually self-making, requiring heat and time. The worker's duty is to watch gauges, indicators, and the like, and he does not perform careful visual work as required in other kinds of plants. The lighting is, therefore, for safety and usually a low intensity is sufficient. Greater intensities should be obtained on gauges, thermometers, and valves by locating lighting units near these important points.

Selection of the proper type of reflecting and diffusing units is a most important item in illumination. Experience shows that the lighting intensities in many plants are far below what they should be for efficient work. The recommended levels of illumination for chemical works according to present-day standards are:

	Foot-Candles
Hand furnaces, boiling tanks, stationary driers, stationary or gravity crystallizing	5–7
Mechanical furnaces, generators and stills, mechanical driers, evaporators, filtration, mechanical crystallizing, bleaching	6–10
Tanks for cooking, extractors, percolators, nitrators, electrolytic cells	10–15
Laboratory	15–20

Vaporproof units employing the plain glass globe have been used most generally throughout chemical plants. This is a wasteful and an ineffective practice because the light is not directed in useful directions. The practice is comparable to the use of bare lamps in other industries—glare is pronounced and the uniformity of illumination poor. The distribution curve of a lamp and a clear glass vaporproof globe is shown in figure 7.

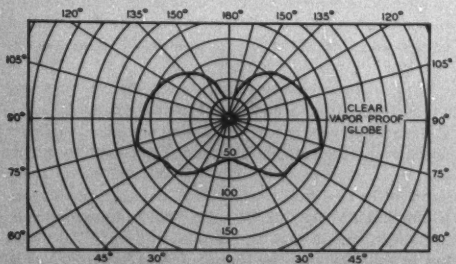


Figure 7. Light-distribution curve for a lamp and clear-glass vaporproof globe

The simplest method of increasing the efficiency of the plain glass globe is to add a porcelain-enameled steel reflector (figure 8). Another method is to use one of the vaporproof prismatic reflector units. The distribution curves (figure 9) show how the light is reflected downward instead of being given off in nonuseful directions.

Where highly explosive fumes, material, or vapor are present, it is essential that all lighting equipment be absolutely tight not only between the globe and fitter or hood, but also between the sockets and conduit system. In some highly dangerous situations, the entire lighting

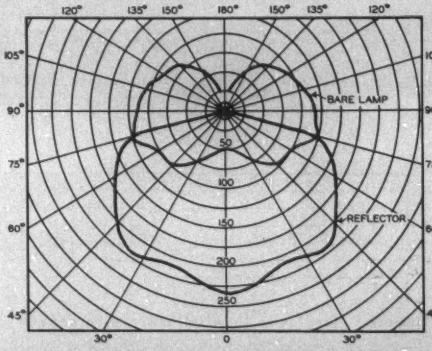


Figure 8. Light-distribution curve showing how a porcelain-enameled steel reflector increases the effective candle power over that produced with the plain glass globe

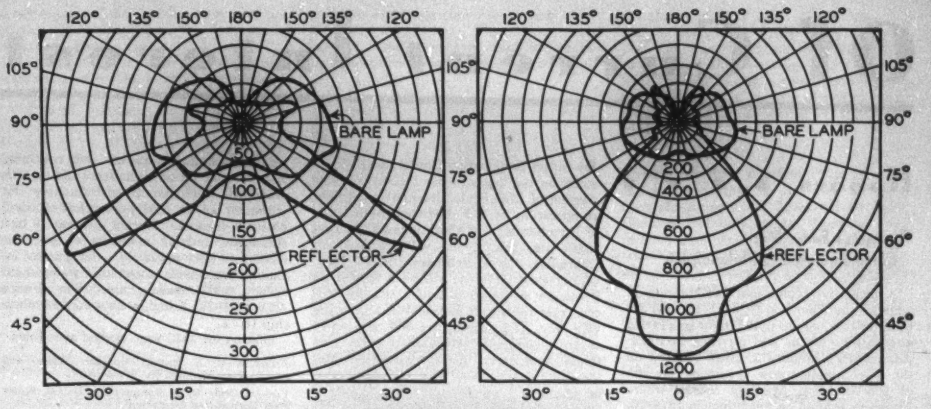


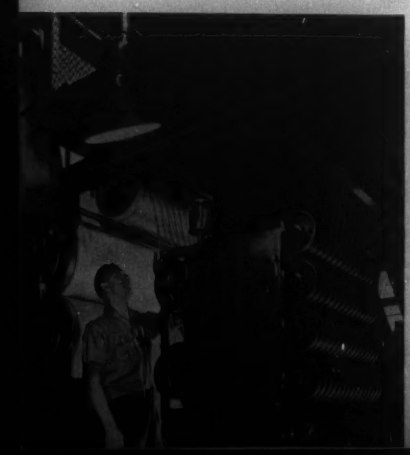
Figure 9. Light distribution curves showing advantage to be gained by using vaporproof prismatic reflector globe instead of plain glass globe

units are mounted outside the buildings and the light is transmitted into the rooms through glass windows. In other cases, where the flash point of the explosive substance is low, vacuum-type lamps in the smaller sizes (100 watts and under) are preferable to type *C* lamps in the larger sizes (100 watts and above). In order to make an absolutely tight fit between the globe and fitter or hood, gaskets are employed.

Fittings or hoods for use with vaporproof units are made of black or galvanized cast iron, silicon-aluminum alloy, or bronze. In general, where explosive material, acid, or excessive moisture are present, either the cast-iron with a black asphalt paint finish or the silicon-aluminum-alloy fittings are practical. Where alkali vapors are present, the galvanized cast-iron fitting is preferable; aluminum fittings should not be used. Where acid fumes are present, a fitter and globe that will withstand the action of acid should be employed. Cast-iron black asphalt-painted or silicon-aluminum-alloy fitters with a reflector or globe and reflector combination should be used. In some extreme acid conditions, lead alloy or Bakelite fittings may be used to advantage.

Wherever possible the illumination in the chemical laboratory should be of the indirect type using daylight lamps for the reason that the light should be well diffused without sharp shadows and should be of approximate daylight color so that the color of the various solutions and precipitates can be accurately judged.

Many chemical plants have extensive yards where pipe lines and passageways are present. In order that fire and accident hazards may be reduced to a minimum and that necessary work may be done in such yards and passageways, they should be lighted to a degree approximating eight times full moonlight intensity (0.2 foot-candle). The most suitable type of lighting unit for this service is a tightly enclosed prismatic reflector mounted on poles or brackets not less than 20 feet high. Spacing between adjacent units should not exceed eight times the mounting height



New Telephone Cable Has 606 More Wires

WITHOUT increasing the diameter of its largest telephone cable from the former size of 2 5/8 inches, the Bell System has increased the number of separately insulated copper wires within the cable from 3,636 to 4,242. The diameter of the wires also remains unchanged. The addition of 303 pairs of wires within the same girth of cable was accomplished by an improved technique of insulation which reduced the thickness of insulation around each wire by 0.003 inch.

The method of insulation, which was invented within the last decade by Western Electric Company, consists of the application of paper pulp directly onto the wire, making a thin coating of paper. Formerly wires for cable had been insulated by wrapping paper ribbon spirally around them. The paper-pulp insulating machine is shown in the illustration.

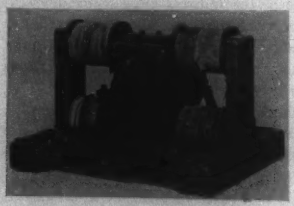
Of Current Interest

Honors • • • •

Thomson's Early Work Commemorated in Philadelphia

A memorial tablet marking the site at which Elihu Thomson (A'84, F'13, HM'28) built his first bipolar dynamo for generating alternating current was unveiled in Philadelphia, Pa., January 3, 1940. Placed on the office building now occupying the site of the Harrison Machine Works where Thomson worked on inventions in 1878–79, the tablet was erected under sponsorship of the Franklin Institute and through the efforts of four of Thomson's early associates, A. L. Rohrer (A'87, M'88), J. R. Lovejoy (A'91, F'13), H. G. Reist (A'90, F'13), and W. J. Foster (A'07, F'16).

The Franklin Institute at the same time opened a display of Thomson's early inventions, including the original bipolar



dynamo, shown in the accompanying illustration, the shell-type transformers, and the vibrating-arc lamp, all developed before 1880.

Education • • •

Iowa State Bulletin Reprints AIEE Paper. The Engineering Experiment Station of Iowa State College issued as its bulletin 142, 1939, "Amplitudes of Magnetomotive-Force Harmonics for Fractional-Slot Windings of Three-Phase Machines" by J. F. Calvert (A'27, M'35). The theoretical development of this work, which was carried out as an experiment-station project, was presented at the AIEE summer convention, Washington, D. C., June 1938, and published in TRANSACTIONS (volume 57, p. 777–85, 1938) under the title "Amplitudes of Magnetomotive-Force Harmonics for Fractional-Slot Windings—I". Copies of the bulletin may be obtained without charge on request to the director of the Iowa Engineering Experiment Station, Ames.

Broadcast Engineering Conference. Sponsored by the department of electrical engineering of Ohio State University, with the co-operation of the National Association of Broadcasters, the third annual broadcast engineering conference will be held at Columbus, Ohio, February 12–23, 1940. Of particular interest will be a session on frequency modulation, and a trip by special train to inspect station WHAS, Louisville, Ky. The conference will also serve as an engineering convention for the National Association of Broadcasters. Further information about the conference may be obtained from Doctor W. L. Everitt, Ohio State University, Columbus.

Engineering College at Duke. The division of engineering at Duke University, Durham, N. C., formerly administered as part of Trinity College, has been reorganized by action of the trustees into the College of Engineering of Duke University. Curricula are offered in civil, mechanical, and electrical engineering. W. H. Hall, professor of civil engineering and chairman of the former engineering division, has been appointed dean of engineering.

Other Societies •

ASA Reviews 1939 Activities at Annual Meeting

Work accomplished by the American Standards Association during 1939, as reviewed at the society's annual meeting, December 13, 1939, included completion of "American Standard Inspection Requirements for Motor Vehicles"; initiation of projects for standards on aeronautics and on photographic equipment; and continuation of work on co-ordinated building-code standards, merchandising standards for consumer goods, and prevention of occupational diseases. During the year 19 new standards and 45 revisions of previous standards were approved. Six groups, including professional societies, a government agency, and a trade group, affiliated with ASA in 1939, bringing its basic membership to 73.

Officers for 1940 were elected as follows:

President—E. A. Prentis, Spencer, White, and Prentis, New York, N. Y. (re-elected).

Vice-president—R. E. Zimmerman, United States Steel Corporation (re-elected).

Chairman, Standards Council—R. P. Anderson, American Petroleum Institute.

Vice-chairman, Standards Council—H. S. Osborne (A'10, F'21) American Telephone and Telegraph Company.

Future Meetings of Other Societies

American Chemical Society. Annual meeting, April 8–12, 1940, Cincinnati, Ohio.

American Institute of Chemical Engineers. 32d semi-annual meeting, May 13–15, 1940, Buffalo, N. Y.

American Physical Society. 233d meeting, February 22–24, 1940, New York, N. Y.

234th meeting, April 25–27, 1940, Washington, D.C.

American Society of Mechanical Engineers. Spring meeting, May 1–3, 1940, Worcester, Mass.

American Society for Testing Materials. Committee week and spring meeting, March 4–8, 1940, Detroit, Mich.

Association of Iron and Steel Engineers. Annual Spring Conference, April 1–2, 1940, Cincinnati, Ohio.

Electrochemical Society. Spring meeting, April 24–27, 1940, Wernersville, Pa.

ECPD Bibliographies. A series of five bibliographies on engineering subjects have been prepared by the committee on professional training of the Engineers' Council for Professional Development. Developed in consultation with more than 100 teachers of technical and engineering subjects, the five individual lists are classified as: Section I, mathematics, mechanics, and physics; Section II, aeronautical and civil engineering; Section III, chemistry and chemical and industrial engineering; Section IV, electrical and mechanical engineering; Section V, metallurgy, mineralogy, geology, and mining engineering. Copies may be obtained for 10 cents a list, or 50 cents for the set, from ECPD, 29 West 39th Street, New York, N. Y.

From AEC • •

ITEMS appearing under this heading are from the news service of American Engineering Council.

American Engineering Council Holds 20th Annual Meeting

Representatives of the member engineering organizations of American Engineering Council met in Washington, D. C., January 11–12, 1940, for the 20th annual assembly of the joint organization. The program included reports of various committees, election of officers, and the annual All-Engineers Dinner, at which Doctor William T. Foster, director of the Pollak Foundation, Newton, Mass., was chief speaker. The 10th annual conference of engineering society secretaries was held concurrently.

In the annual report of the executive secretary, F. M. Feiker (M'34) summarized the work of AEC committees and staff and reported upon the plans under consideration for restating the objectives and reorganizing the work of AEC. (These activities and

other aspects of AEC action have been reported at various times in ELECTRICAL ENGINEERING.)

Election of officers took place at the annual business meeting, at which were present as AIEE representatives F. M. Farmer (A'02, F'13, president), C. O. Bickelhaupt (M'22, F'28), and National Secretary H. H. Henline (A'19, M'26) *alternate*. AEC officers for 1940 are: *president*, A. J. Hammond; *vice-presidents*, W. L. Bott, D. H. Sawyer, C. O. Bickelhaupt (M'22, F'28) and J. S. Dodds (last two re-elected); *treasurer*, L. J. Fletcher. F. M. Feiker resigned as executive secretary, effective July 1, 1940, to become dean of engineering at George Washington University; his successor has not yet been chosen. A biographical sketch of Mr. Feiker appears on page 89 of this issue.

Power Capacity Growing

As of September 30, 1939, the installed capacity of all electric generating plants reporting to the Federal Power Commission aggregated 40,203,969 kilowatts, an increase of 1,161,864 kw, or 3 per cent, since December 31, 1938. Of the total, 85.7 per cent comprise generating stations owned by private utility companies serving the public, 11.6 per cent publicly owned plants, and 2.7 per cent those operated by railroads and other agencies not distributing to the public. Hydroelectric plants accounted for 11,353,925 kw; steam and internal combustion plants for 28,850,044 kw. Of the net increase, hydro totalled 287,862 kw, while steam and internal combustion units increased by 874,002 kw.

Recent major hydroelectric installations reported to the FPC consist of one privately owned 75,000-kw plant in Virginia and a 165,000-kw addition to the generating capacity at Boulder Dam. All other additions in the hydro class were in units of less than 25,000 kw. In steam generation, two private companies reported additions in excess of 50,000 kw, and a municipal plant installed an additional 30,000-kw unit.

Industry • • • •

Air-Conditioning Units for Home and Office Use

Three air-conditioning units designed for home and office use and priced for the consumer market have recently been developed by Westinghouse Electric and Manufacturing Company. The smallest of the three units, shown in the illustration, has a cooling capacity of 4,000 Btu per hour and is expected to be used chiefly in bedrooms. The next larger model, with a capacity of 6,000 Btu per hour, and total conditioned-air delivery of 225 cubic feet per minute, is planned for use in average private offices under the heavier requirements of daytime service. The largest of the line is a floor model for larger offices and private houses, with 8,500 Btu capacity and delivery of 300 cubic feet of conditioned air per minute.

The new units, called "Mobilaires," require no plumbing connections, only floor plugs, for installation. The window units may be installed without removing radiators and can serve as ventilators when cooling is unnecessary. Powered by hermetically sealed condensing units, they are as quiet in operation as a modern 16-inch electric fan, according to the manufacturers.

Stone and Webster 50th Anniversary. Founded in 1889 and still guided by Charles A. Stone (A'91, M'07) and Edwin S. Webster (A'91, M'07), two young electrical engineers who had graduated from Massachusetts Institute of Technology the previous year, the firm of Stone and Webster, Inc., celebrated its 50th anniversary during the closing week of 1939. Centering originally in the field of electric utility construction, the firm's work subsequently spread to embrace also financing and valuation work as well as the active operation and management of a variety of utility properties. The firm has been active from coast to coast.

Another Air-Blast Breaker. The first special demonstration of the new air-blast-type circuit breakers developed by Allis-Chalmers Manufacturing Company was recently given to a group of about 30 electrical engineers at the company's switchgear laboratory in Milwaukee, Wis. Following operating tests, the visitors examined the circuit breaker at close range. A demonstration of air-blast circuit breakers by General Electric Company at Schenectady, N. Y., was reported in the September 1939 issue.

Television Handbook. "Look and Listen" by M. B. Sleeper, a 96-page booklet covering the status of the television art and the design and construction of equipment, has been issued by The Norman W. Henley Company, 2 West 45th Street, New York, N. Y. Planned for both technician and lay reader, it contains general information as well as details of set building, installation, and servicing, and is illustrated. Copies may be obtained from the publisher, price, with spiral binding, $1.00; cloth, $1.50.

Aluminum Company of America announced December 24, 1939, that the company had contracted for 32,500 kw of Bonneville power ($500,000 annually) for 20 years, and expected to begin work soon on a $3,000,000 reduction plant just west of Vancouver, Wash.

Letters to the Editor • • •

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

Membership Participation in AIEE Elections

To the Editor:

Referring to President Farmer's communication in the November 1939 issue of ELECTRICAL ENGINEERING, concerning our election procedure, it is quite true that there has been a feeling that elections of officers are too much cut and dried in the AIEE with insufficient direct voice from the members.

The balloting is all set up in committees as explained in the article. This corresponds in a measure to the procedure in our national government, whereby national conventions nominate candidates. But with this difference—that in our government we have a party system of nomination and election, generally with one party in, and another party of the opposition, out.

In AIEE there is no set-up for an "opposition" party. This corresponds to conditions in totalitarian governments, where a person who disagrees with the party in power is just out of luck. Other large technical associations go about the matter of electing officers in just about the same way as we do in AIEE.

Representative government depends upon electing officers to govern on the basis that an elected group, small in numbers, is fitted to decide questions of state better than the mass of the voters. Recall, for not representing public opinion, is through subsequent elections by the efforts of an opposition party. This opposition party element, therefore, is ab-

solutely essential to our national form of government, without which we would become as Germany or Russia, and the party in power would perforce be self-perpetuating.

Except for the somewhat hazy provision for other candidates on the ticket, if proposed by 25 or more members, it would seem to be just about as well to let the presidents be elected by the nominating committee for all the difference it would make. If this nominating committee is truly representative of the membership, a direct popular vote would seem unnecessary. According to the United States Constitution, voters do not vote for the president and vice-president direct, but vote only for "electors," who in turn elect the President.

In national politics, parties represent either opposed controversial viewpoints or opposed personalities. In our AIEE, we do not have opposed policies but may have a choice of personalities.

The present method of setting up a "cut-and-dried" ticket and asking the members to vote in addition, is neither the representative method nor a bona fide direct election. It is largely responsible for the general feeling of dissatisfaction.

All of which leads to the suggestion that if a direct election by mail is continued, the nominating committees offer our members the choice of three candidates for the important offices with a statement outlining the history, affiliation, and previous activities on behalf of the AIEE. I say three, because if there were only two, a defeated candidate might feel unduly humiliated. The second in number of votes would be vice-president, etc.

I think that this method would at least be conducive to a more satisfied feeling on the part of many members. It would retain the best features of both the representative form and the direct form of elections.

PAUL MACGAHAN (A'02, M'15)

(Development engineer, meter department, Westinghouse Electric and Manufacturing Company, Newark, N. J.)

Specific Articles on Social Questions

To the Editor:

During the last few years ELECTRICAL ENGINEERING has published a number of articles on the social side of engineering. These have all been interesting and informative, but I should like to see them go one step further. Why not go from the general to the specific? There are many social questions today the ultimate outcome of which will profoundly affect engineering in almost every phase. While the general press has not hesitated to print anything on the subject, even to the point of preferring sensationalism to veracity, the technical press has been content either to ignore the problem entirely or at best to deal only in generalities.

I should like to see a full, frank discussion of such things as the present social-security legislation, public-utility regulation, profit-sharing systems, labor organization, etc., particularly in their relation to the profession. While it may be difficult to get one individual to present an unbiased opinion on any of these subjects, it should be possible to find competent engineers on all sides of these issues. A symposium every few months on one of these controversial subjects would be of value and interest to the membership.

I am sure that everyone realizes the problems involved in trying to present an impartial view on such topics and will make due allowances if some of the articles do not coincide with their own opinions.

Of course the AIEE should not take sides on any of these issues, but it seems to me it is one of the functions (although only a minor one) of an engineering publication to keep abreast of social developments.

DANIEL E. ROBB (A'39)

(Aircraft radio laboratory, Wright Field, Dayton, Ohio)

Currents and Voltages of a Three-Phase Unbalanced Load

To the Editor:

In the computation of the phase voltages and currents of an unbalanced three-phase wye load, the electrical engineer usually employs one of several generally accepted methods.

He may follow the method described in "Alternating Currents and Alternating Current Machinery," by D. C. and J. P. Jackson. In this case, one of the phase voltages will be expressed as the sum of two unknown scalars in quadrature, viz. $e_1 = a + jb$ where a and b are the two unknowns. Since the line voltages are known, the remaining phase voltages may also be determined as functions of a and b. Each phase current may then be expressed as the product of the phase voltage and its phase admittance. But since the neutral is not grounded, the sum of the phase currents must equal zero, so that by suitable factoring the following expression is obtained:

$$\Sigma i = f_1(a,b) + jf_2(a,b) = 0$$

or

$$f_1(a,b) = 0, \qquad f_2(a,b) = 0$$

The two simultaneous linear equations may then be solved for a and b in the conventional manner.

The advantage of this method is that it is methodical and easily adaptable to schedule form. Unfortunately, there are many opportunities for errors to occur because of the large number of operations. For example, the solution of a single phase voltage requires about 21 multiplications, 21 divisions, and 17 additions. This is a total of 55 operations, each of which could involve a mistake. Another disadvantage of this method is that since only scalar quantities are used, the advantages of the vector slide rule cannot be fully realized.

A method using vector quantities, and hence much more adaptable to the vector slide rule, is that described by Bryant, Correll, and Johnson in their "Alternating Current Circuits." Here, the vector residual is taken as the unknown. (The residual is the voltage difference between the common point and the true neutral.) As in the first method, expressions for the phase voltages and phase currents are first found. The sum of the phase currents is equated to zero and the resulting equation then solved for the residual. All other quantities are then obtained from this particular value of residual.

A general solution based on Kirchoff's law and employing conventional current-mesh equations also may be used as described in "Alternating Current Circuits" by M. P. Weinbach.

All these methods lack directness and brevity. A method which is both direct and excellently suited to the vector slide rule is described as follows:

Let the three lines be characterized by the numbers 1, 2, and 3. The line voltages are then E_{1-2}, E_{2-3}, E_{3-1}; the phase voltages are e_1, e_2, e_3; and the respective phase admittances are Y_1, Y_2, and Y_3. Using general numbers, the following equations may then be written,

$$\begin{aligned} E_{1-2} &= e_1 - e_2 \\ E_{2-3} &= e_2 - e_3 \\ E_{3-1} &= e_3 - e_1 \end{aligned} \tag{1}$$

Expressing all phase voltages in terms of e_1,

$$\begin{aligned} e_1 &= e_1 \\ e_2 &= e_1 - E_{1-2} \\ e_3 &= e_1 - E_{1-3} \end{aligned} \tag{2}$$

Also

$$\begin{aligned} i_1 &= e_1 Y_1 \\ i_2 &= (e_1 - E_{1-2}) Y_2 \\ i_3 &= (e_1 - E_{1-3}) Y_3 \end{aligned} \tag{3}$$

Since, by hypothesis, there is no neutral return,

$$i_1 + i_2 + i_3 = 0$$

Or

$$e_1 Y_1 + (e_1 - E_{1-2}) Y_2 + (e_1 - E_{1-3}) Y_3 = 0 \tag{4}$$

Solving for the phase voltage, e_1, and deriving expressions for e_2 and e_3 in a similar manner, the following equations result:

$$e_1 = \frac{E_{1-2} Y_2 + E_{1-3} Y_3}{Y_1 + Y_2 + Y_3} \tag{5}$$

$$e_2 = \frac{E_{2-1} Y_1 + E_{2-3} Y_3}{Y_1 + Y_2 + Y_3}$$

$$e_3 = \frac{E_{3-1} Y_1 + E_{3-2} Y_2}{Y_1 + Y_2 + Y_3}$$

Similarity to dyadic notation will be noted in the subscripts; the first subscript of each numerator voltage is the same as the phase voltage; the second subscript indicates the correct admittance multiplier. Therefore, the rule for obtaining each expression is: Compute each Y by forming the reciprocal of the Z. Determine the line voltage from the phase in question to each of the remaining two phases. Multiply each of these two line voltages by their respective terminating phase admittances. The sum of these two products divided by the sum of the three phase admittances gives the phase voltage in question. Since all other unknowns may be obtained from e_1 in steps 2 and 3, only e_1 need be found. However, as a check, e_2 and e_3 may be found with but little additional computation.

It is of interest to note that this method gives one of the desired unknowns immediately, there being no necessity to find

first simultaneous linear equations, the residual, or the system's impedance matrix. Consequently, the method requires only about 28 operations (such as addition, subtraction, multiplication, division, or slide-rule settings), whereas the other methods given will require from 50 to 60 operations. Also, since the derivation is general with respect to them, the line voltages may be unbalanced. The first method becomes complicated when used on unbalanced voltages because of the irrational numbers involved. The second method described, likewise, is unsatisfactory, because the voltage residual for unbalanced line voltages has but little meaning and would be difficult to determine.

Therefore, the advantages of the method derived here may be enumerated as follows:

1. It is especially suited for computation on the vector slide rule.

2. It requires a minimum of operations, thus reducing the opportunity for mistakes to occur.

3. It may be used with unbalanced line voltages provided the equation $E_{1.3}+E_{2.1}+E_{3.1}=0$ is satisfied.

4. The simple rule governing subscripts makes the equations extremely easy to remember.

W. H. HUGGINS (Enrolled Student)

(School of engineering, Oregon State College, Corvallis)

Union Pacific's New Steam-Electric Locomotive

To the Editor:

In the article entitled "Union Pacific's New Steam-Electric Locomotive," appearing in the October issue of ELECTRICAL ENGINEERING, there are several statements from which it might be inferred that the steam-turbine-electric locomotive was an entirely new development in railroad engineering, reflecting much co-operative research and design in the U. S. A.

This will be, of course, true of the unit described but may be misleading as a general statement, for the steam-turbine-electric locomotive has long had the serious attention of designers and builders in other countries.

In 1921 Sir Vincent Raven, then chief mechanical engineer of the North Eastern Railway Company, built a locomotive of this type which was in use for a number of years, receiving modifications from time to time; it incorporated a water-tube boiler, Parsons turbine and generator, fan-cooled system of condensers, series-wound motors, etc.

Others have followed; notably on the Swedish State Railways, which have employed the Ljungstrom turbine as prime mover. They have been fully described in the English and European technical press, and their details and performances are, doubtless, known to American locomotive engineers. Economic results attained with their use on regular main-line operation, for various periods over the past 17 years, have not hitherto justified them as serious competitors to steam and Diesel-electric locomotives under European conditions.

It may well prove that the quite different conditions for which the Union Pacific locomotive has been designed are those in which the steam-turbine-electric locomotive will find its true field; nevertheless the writer views with some doubts the claims and expectations appearing in the article on behalf of this very modern traveling power station carrying one customer.

Its very high-speed turbine and gearing, and wealth of automatic and interlocking details on the steam-raising plant, to name but a few of its novel features, do represent an advance in the art; whether they can stand up to the exacting conditions imposed by regular railroad schedules and justify themselves economically can hardly be known for some years ahead. That is, of course, the reason for which this locomotive has been built; if in, say, the year 1942, or happily earlier, the Union Pacific places further orders for similar or better locomotives of this type, then its sponsors may well receive the congratulations of the railroad world.

The steam-electric locomotive is a lineal descendant of the gas-electric and Diesel-electric types, which owe much of their early development to work done in England on engines for tanks during the Great War. As far as the writer is aware the first gas-electric locomotive to appear in North America was that brought out by the Canadian Pacific in 1925, which made a return transcontinental journey in very remarkable time on its first appearance. It followed a successful English design, and some of its equipment, including the prime mover, was, I believe, made in Scotland.

T. ALAN ROSS (M'24)

(c/o Lloyd's Bank, Ltd., 6, Pall Mall, London)

Library • • • •

OPERATED jointly by the AIEE and the other founder societies, the Engineering Societies Library, 29 West 39th Street, New York, N. Y., offers a wide variety of services to members all over the world. Information about these services may be obtained on inquiry to the director.

The following new books are among those recently received at the Engineering Societies Library. Unless otherwise specified, books listed have been presented by the publishers. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books in question.

GRAPHIC PRESENTATION. By W. C. Brinton. New York, Brinton Associates, 1939. 512 pages, illustrated, 9½ by 6 inches, fabrikoid, $5.00. A brief encyclopedia of methods for representing facts graphically, which covers maps, geneological charts, statistical charts, etc. Each variety is represented by specimens, with explanations of their uses and interpretation. The use of color is covered. In addition practical advice is given on equipment and methods for making graphs and exhibits, on reproduction, and on the use of graphic material. Glossary.

SCIENCE AND MECHANISATION IN LAND WARFARE. By D. Portway. New York, Chemical Publishing Company, 1939. 158 pages, diagrams, charts, 9 by 6 inches, fabrikoid, $2.50. Intended for students in the Cambridge University Officers' Training Corps, this book supplies, in non-technical language, the principles and some of the details underlying the scientific side of modern warfare. The several chapters are devoted to a description of fundamental scientific principles, the importance of railways in war, the various aspects of mechanization, weather problems, chemical warfare, the work of the army engineer and the signal corps, the artillery survey, and some problems of personnel.

THE SENIORITY PRINCIPLE IN UNION-MANAGEMENT RELATIONS. By F. H. Harbison. Princeton, N. J., Industrial Relations Section of Princeton University, 1939. 39 pages, 10 by 7 inches, paper, $0.75. This study, based largely upon personal interviews with employers and labor leaders, is a digest of experience and opinion on selected aspects of the seniority problem as it applies to the relations of union and management in the mass-production industries. It summarizes the reasons for the demand for seniority rights in trade-union agreements, the degree to which seniority is modified by other factors, and the manner in which these modified rights are applied.

SOCIAL FUNCTION OF SCIENCE. By J. D. Bernal. New York, Macmillan Company, 1939. 482 pages, charts, tables, 9 by 6 inches, cloth, $3.50. Sketches briefly the historical development of science, and considers its present organization, pointing out reasons for the present confused and inefficient status of scientific research and showing the forces of prejudice which act in opposition to it. Suggests ways of reorganization with the object of increasing the benefits society can gain from scientific activity.

ENGINEERING MATERIALS. By A. H. White. New York and London, McGraw-Hill Book Company, 1939. 547 pages, illustrated, 9 by 6 inches, cloth, $4.50. The greater part of this book is devoted to the manufacture, heat-treatment, fabrication, and properties of iron, steel and the non-ferrous metals, with consideration of the effect of methods of fabrication on the physical properties. Subsequent chapters present information on clay products, lime and cements, fuels, water and its industrial utilization, corrosion and protective coatings, and plastics. References accompany each chapter.

THE CONSTRUCTION OF NOMOGRAPHIC CHARTS. By F. T. Mavis. Scranton, Pa., International Textbook Company, 1939. 132 pages, diagrams, etc., 8½ by 5 inches, fabrikoid, $2.00. Provides a practical course for engineers and advanced undergraduate students, discussing the theory of logarithms, the slide rule, and functional co-ordinate papers. Many examples of nomogram construction are included.

HOUSING FOR THE MACHINE AGE. By C. A. Perry. New York, Russell Sage Foundation, 1939. 261 pages, illustrated, 9 by 6 inches, cloth, $2.50. Compares methods of construction of houses and of automobiles with a view toward mass production. The neighborhood unit is examined, and the results of practical experience are set forth, with particular attention to the matter of assembling large plots in metropolitan districts. The final chapter discusses the social significance of the unit.

BUSINESS CYCLES. Two volumes. By J. A. Schumpeter. New York and London, McGraw-Hill Book Company, 1939. 1095 pages, charts, 9 by 6 inches, cloth, $10.00. An analysis of the causes and the mechanism of business cycles is presented, with a detailed discussion of statistical and historical material covering the past 150 years. These materials are arranged to form a series of exercises in the diagnosis of business situations.

ELECTRICAL TRANSMISSION AND DISTRIBUTION OF POWER. By H. V. Carpenter. Pullman, Wash., Students' Book Store, 1939. 84 pages, mimeographed, diagrams, etc., 11 by 8 inches, cardboard, $2.00. Covers the physical properties of transmission lines, the regulation of both low- and high-voltage lines, materials for overhead lines, choice of voltage, and the mechanical features of power lines. New methods of predetermining corona losses and of plotting catenary relations are included.

MACRAE'S BLUE BOOK. 47th annual edition, 1939–40. New York, MacRae's Blue Book Company, 3616 pages, illustrated. 11 by 8 inches, cloth, $15.00. The forty-seventh annual issue, while subject to the customary revision of the information, follows the established pattern. It provides an index of manufacturers and wholesalers and their local distributors, with addresses; indexed classified list of manufacturers; directory of commercial bodies, banks, railroads, and warehouses in towns of 1000 or more population, and list of trade names.

MY 50 YEARS IN ENGINEERING. By R. A. Hitchcock and M. Weed, with introduction by C. F. Kettering. Caldwell, Idaho, Caxton Printers, Ltd., 1939. 222 pages, illustrated, 9½ by 6 inches, cloth, $3.00. The life, work, and reminiscences of an engineer and teacher, whose working life has spanned a period of extremely rapid development in technical lines, presented in autobiographical form. His activities included railroad, steam power plant, and electric power work, "human engineering," and teaching.

PATENT FUNDAMENTALS. By A. Schapp, Schapp and Coie, San Francisco, Calif.; New York, Industrial Press, 1939. 176 pages, diagrams, 9 by 5 inches, cloth, $2.00. A non-technical explanation of what constitutes true invention is given, with practical examples. Other topics covered include procedure in obtaining adequate patent protection, drafting of effective claims, making assignments, and issuing licenses. Essential facts about trademarks and copyrights are presented.

Institute Activities

National • • • •

Columbia Scholarship in Electrical Engineering

The governing bodies of Columbia University annually place at the disposal of the AIEE a scholarship in the graduate course in electrical engineering at Columbia University's school of engineering. The scholarship pays the annual tuition of $380. Its renewal for the completion of the course is dependent upon the standard of work maintained by the holder.

The graduate course in electrical engineering at Columbia may be either elective, leading to the degree of master of science, or prescribed, leading to that of electrical engineer. Candidates for the scholarship must fulfill the regular admission requirements for the course chosen, details of which will be sent on request by the secretary of the University, or the national secretary of the AIEE. No special examination is required.

Applicants for the scholarship for the academic year 1940–41 should send their qualifications to the National Secretary, AIEE headquarters, before June 1, 1940. Letters should state the candidate's age, birthplace, education, pertinent activities such as athletics or self-help in college, and references, and should enclose a photograph. A committee composed of W. I. Slichter, chairman, Francis Blossom, and H. C. Carpenter will consider the applications and report their selection to the University. Other qualifications being equal, preference will be given to members of AIEE Student Branches.

Winter Convention to Be Reported in March Issue

As this issue goes to press, the Institute's 1940 winter convention is under way at New York, with every evidence of continuing the successful record of winter conventions. Registration for the first two days totaled 1,178, compared with 1,159 for the first two days of the 1939 convention, 1,027 for 1938, and 827 for 1937.

On Wednesday evening, January 24, the Edison Medal was presented to Philip Torchio (A'95, F'12) and the Hoover Medal to Gano Dunn (A'91, F'12). Following the medal presentations, Doctor Enrico Fermi delivered a lecture on "Nuclear Disintegrations", the essential substance of which is published on pages 57–8 of this issue. The March issue will contain the full report of the convention.

Future AIEE Meetings

Summer Convention
Swampscott, Mass., June 24–28, 1940

Pacific Coast Convention
Los Angeles, Calif., August 26–30, 1940

District • • • •

Executive Committee of District 6 Meets

Revision of the existing regulations for grading student papers presented for the District Branch paper prizes was recommended at the annual meeting of the North Central District (6) executive committee, held at Omaha, Nebr., December 2, 1939. With the present method of grading undergraduate papers in the same manner as papers for National prizes, the heavy weighting given the factors, "Value in Its Field" and "Value to Electrical Engineering" was regarded by the committee as tending to discourage student competition. The committee voted unanimously that the matter be taken up with the national secretary.

A. L. Turner, District vice-president, was selected to represent the District on the National nominating committee.

The District will support the efforts of the Denver Section to have the 1941 summer convention held in that city. The only District meetings to be held during 1940, it was decided, will be the annual executive committee meeting, and the annual Student Branch Conference, the latter to be held at Grand Forks, N. Dak., April 19–20, 1940.

Noting that several Branches had held meetings at which the Scott anniversary film was shown, the committee decided to remind other Branches of the film's availability. Membership activities, Section co-operation with local societies, and other matters of District business were also discussed.

Section • • • •

Charleston Section to Be Formed

Formation of a Charleston, W. Va., Section was authorized by the AIEE executive committee at its meeting on December 11, 1939 (*EE, Jan. 1940, p. 43*). The new Section, 68th to be formed, will have a territory of 23 counties in West Virginia.

The following items are contributed by C. A. Faust, Mansfield, Ohio, for the Sections committee

Madison Section Organizes Rock River Valley Subsection

At the request of 14 AIEE members and 25 local members from Rockford, Ill., Freeport, Ill., and Beloit, Wis., the Madison, Wis., Section has established the Rock River Valley Subsection at Rockford to serve the members in this area. The formal proposal to organize the new division was made at the November 10 meeting. Official authorization was granted at the December 15 meeting, held at the Hotel Faust in Rockford.

To provide for the establishment and conduct of Subsections, section 12 was added to the bylaws of the Madison Section. It provides that:

Subsections may be proposed by the executive committee or by 10 members and must be confirmed by a majority vote at the following Section meeting; Subsection meetings supplement regular Section meetings; meetings and programs are planned by Subsection officers, but finances are handled through the Section, which will pro-rate to Subsections not over 25 per cent of the annual Section income; Subsection chairmen are ex officio members of the Section executive committee; Subsection policies and expenditures are to be in accordance with AIEE requirements.

"Electricity in War" Washington Section Theme

Instead of selecting a variety of widely divergent subjects for its technical sessions, the Washington Section chooses one theme for a fiscal year, using all the technical meetings to develop it completely. Recognizing that war is the subject of greatest interest to the world today, the technical sessions committee selected "Electricity in War" as the theme for 1939–40.

To carry out the theme, a series of three programs is being held: electricity in aviation, electricity in the navy, and electricity in the army. Each program is divided into three sessions: a lecture meeting, an inspection trip, and a discussion meeting. Informal speakers' dinners, attended by the Washington Section executive and technical sessions committees, are held prior to the lecture and discussion meetings. Refreshments are served after these meetings. The notices for the technical sessions are being printed with a distinctive color to differentiate them from the regular meeting notices.

The "electricity in aviation" program, held before Christmas, was very favorably received, 140 attending the lecture meeting, 175 the inspection trip, and 130 the discussion meeting.

At the lecture meeting three authorities

spoke on "Electric Power in Aircraft," "Analysis of Power Generation and Distribution Problems in Aircraft," and "Certain Features of Aircraft Radio-Communication Systems and Equipment." The inspection trip was made to the Bolling Air Field Station. The discussion meeting, under ten leaders, covered electric versus hydraulic and other power, main versus auxiliary engine generator drives, generator units, a-c and d-c power in aircraft, electrically operated aircraft ordnance equipment, electrical system design, military aircraft transmitters, aircraft radio receivers and direction finders, blind landing, and radio aircraft radio operation.

More Sections Announce Season's Programs in Advance

In addition to the eight Sections named in the January issue which distribute programs for the season prior to the first meeting, three more Sections—Milwaukee, Houston, and Oklahoma City—complete their season's programs in time to give the details to the members early in December.

Milwaukee prints the full program on a 4-page 3- by 5 1/2-inch white folder and includes the names of all officers and committee members.

Houston prints its program on a letter-size sheet and suggests that it be placed "under the glass on your desk." This schedule of meetings is distributed with a news letter containing other information of interest.

Oklahoma City announced the details of the remaining five meetings of the season on the notice for its December meeting.

St. Louis and Memphis Sections Award Attendance Prizes

To increase attendance at meetings and to provide a bit of entertainment in addition to the regular programs, some Sections of the Institute present a prize to a member at each meeting. St. Louis has had this custom for 10 or 12 years, and Memphis has used it for more than 4 years.

The St. Louis practice is to place membership cards in a box, have one drawn, and if the member whose name is drawn is present and wearing a badge with his name on it, he receives a prize. Prizes are usually electrical appliances donated by local dealers. The custom of wearing badges was adopted to help new members get acquainted, and is encouraged by the prize system.

Memphis has a $2 prize drawing at each monthly meeting. Five names are drawn, the fifth being the winner. If the winner is not present the prize is carried over and added to that for the next meeting. When the accumulated prize money reaches $10, names are drawn until one of the members present wins, and the prize for the next meeting is again $2. The amount of the prize is stated on meeting notices, and the Section secretary has noted that attendance increases with the prize.

Holiday Activities. An informal Christmas party was held by the North Texas Section for members and women guests on December 18, at the Baker Hotel, Dallas. Members of the St. Louis Section received a Christmas greeting on the gaily decorated notice for the December 13 meeting. The Denver Section sent greeting cards showing a mountain scene to Section members and nonmember friends of the Section.

Personal • • •

F. M. Feiker (M'34) executive secretary, American Engineering Council, has been appointed dean of the school of engineering, George Washington University, Washington, D. C. A native (1881) of Northampton, Mass., he received the degree of bachelor of science in electrical engineering in 1904 and the honorary degree of doctor of engineering in 1938 from Worcester Polytechnic Institute. After a year as research assistant at that institution, and two years of technical journalism with the General

F. M. FEIKER

Electric Company, Schenectady, N. Y., he became technical editor and later managing editor of *Factory*, and in 1912 chairman of the editorial board of A. W. Shaw Company, Chicago, Ill., publishers of *Factory* and *System* magazines and of technical books. He joined the McGraw-Hill Publishing Company, New York, N. Y., in 1915, as editor of *Electrical World*, eventually becoming vice-president and editorial director of the company. He was assistant to the United States secretary of commerce 1921–22, operating vice-president of the Society for Electrical Development, New York, 1922–26, and managing director, Associated Business Papers, New York, 1926–30. He then became director of the Bureau of Foreign and Domestic Commerce, Washington, D. C., and from 1932 to 1934 directed the educational survey of the Textile Foundation, Washington. Since 1934 he has been with AEC. He is also a member of The American Society of Mechanical Engineers.

W. B. Kouwenhoven (A'06, F'34) dean of engineering, Johns Hopkins University, Baltimore, Md., has been appointed chairman of the AIEE Lamme Medal committee, succeeding E. W. Allen, who died January 1, 1940. He has been a member of th committee since 1938. Doctor Kouwenhoven holds the degrees of electrical engineer (1906) and mechanical engineer (1907) from the Polytechnic Institute of Brooklyn, and a diploma in engineering (1913) and the degree of doctor of engineering (1914)

W. B. KOUWENHOVEN

from Karlsruhe Technische Hochschule, Baden, Germany. He was assistant in physics 1906–07 and instructor in physics and electrical engineering 1907–10 at Brooklyn Polytechnic Institute, and instructor in electrical engineering 1913–14 at Washington University, St. Louis, Mo. He joined the electrical-engineering department of Johns Hopkins University in 1914 as an instructor, becoming associate in 1917. After a leave of absence in 1919–20 as engineering superintendent of the Winchester Repeating Arms Company, New Haven, Conn., he returned to Johns Hopkins as associate professor of electrical engineering, becoming professor and assistant dean of the school of engineering in 1930, and dean in 1938. He has served the Institute as a vice-president (1931–33), director (1935–39), member of the committees on telegraphy and telephony, electrophysics, Sections (chairman 1927–30), co-ordination of Institute activities, technical program, and award of Institute prizes, and is currently a Student Branch counselor, and member of the Edison Medal committee, and the committees on safety, electrochemistry and electrometallurgy, instruments and measurements (chairman 1933–36), and research (chairman 1936–38).

W. S. Conlon (A'20, M'28) has resigned as executive secretary of the National Society of Professional Engineers, Washington, D. C. and opened his own office as consulting engineer in that city. He is one of the founders of the society and was its first treasurer, 1934–35, and since 1935 has been executive secretary in charge of its Washington office. Before going with the NSPE he was city engineer, City of Stamford, Conn.

Tomlinson Fort (A'27, M'35) has been made assistant manager of central-station sales, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. He has been with the company since 1923, when he entered the student course, and since 1931 had been engaged in central-station work at New York, N. Y., where he was active in affairs of the AIEE New York Section.

G. M. Miller (A'21, M'26) formerly superintendent of electrical distribution and construction, Louisville Gas and Electric Company, Louisville, Ky., has been appointed electrical engineer of the company. **J. F. Miller** (A'31,M'38) formerly assistant superintendent of electric distribution, has been made superintendent, and **V. L. McKinley** (A'27, M'34) formerly meter engineer, has been made assistant superintendent. Other changes in the company are transfers from the electrical-distribution department of **H. L. Lowe** (A'30, M'38) to the position of engineer in the electrical engineer's office, and of **F. W. Russell** (A'26) to the position of engineer in the general superintendent's office; promotion of **M. S. Winstandley** (A'29) to the position of electrical construction engineer; and appointment of **C. M. Ewing** (A'26) as assistant superintendent of electrical production.

R. A. Jones (A'20, M'39) has been appointed district engineer, New York district, General Electric Company. He has been with the company since 1916, when he entered the test course at Schenectady, and since 1938 had been assistant district engineer at New York, N. Y. He is succeeded in that position by **W. S. Hill** (A'25, M'30), who has been with General Electric since entering the test course in 1923.

D. D. Knowles (M'39) since 1937 director of research and development, Raytheon Production Corporation, Newton, Mass., has joined the research engineering staff of the special products department of Westinghouse Lamp Division, Bloomfield, N. J. He was formerly associated with the Westinghouse company at East Pittsburgh, Pa., from 1923 to 1937.

R. D. Mailey (F'30) formerly vice-president-General Electric Vapor Lamp Company, Hoboken, N. J., until the merger with the company's incandescent lamp department at Cleveland, Ohio, has been transferred to the lamp development laboratory at Cleveland to supervise various phases of development of gaseous-discharge lamps.

H. S. Osborne (A'10, F'21) operating results engineer, American Telephone and Telegraph Company, New York, N. Y., has been elected vice-chairman of the Standards Council of the American Standards Association. An Institute director and finance-committee chairman, he is one of three AIEE representatives on the Council.

A. L. O'Bannion (A'21, M'28) formerly electrical engineer of the Sumner traffic tunnel at Boston, Mass., has been made superintendent of the fire-alarm division of the Boston Fire Department. His previous experience includes both industrial and teaching positions.

H. E. Smith (A'25) formerly supervising design engineer, Commonwealth Edison Company, Chicago, Ill., has been made line design engineer. He has been with the company since 1917, except for military service.

R. K. Hellman (A'37) formerly with Transatlantic Research and Information Service, Inc., New York, N. Y., is now an electrical engineer for Connecticut Telephone and Electric Corporation, Meriden, Conn.

W. A. Buchanan (M'36) formerly plant wire chief, Chesapeake and Potomac Telephone Company of West Virginia, Charleston, has been appointed district plant manager at Charleston.

F. A. Kartak (A'10, F'33) dean of engineering, Marquette University, Milwaukee, Wis., has been elected president of the Engineers' Society of Milwaukee.

Obituary • • •

Henry Latham Doherty (A'98, M'02, F'13) president and founder, Cities Service Company, died December 27, 1939, at Temple University Hospital, Philadelphia, Pa. He was born May 15, 1870, in Boone County, Ind. He never received a formal technical education, but was awarded the honorary degrees of doctor of engineering from Lehigh University, doctor of laws from Temple University, and doctor of science from the University of Miami. At the age of 12 he became an office boy for the Columbus, Ohio, Gas Company, and advanced through various positions to become assistant general manager of that company. In 1896 he became general manager and engineer of the Madison (Wis.) Gas and Electric Company. During the period 1898–1904 he was chief engineer for various properties of the McMillin interests, in St. Paul, Minn., San Antonio, Tex., and Denver, Colo. In 1905 he organized Henry L. Doherty and Company, bankers and operators of public utilities, and in 1910 founded the Cities Service Company, parent of nearly 200 oil, traction, light, gas, and power subsidiaries throughout the United States. He received the first Beill Gold Medal of the American Gas Light Association in 1898; was a member of the organization board of the World's Congress of Electricity, St. Louis, Mo., 1904; and in 1930 was awarded the Walton Clark Medal of the Franklin Institute for his work in the development of the manufactured gas industry. In 1937 he was awarded the Anthony F. Lucas Medal of the American Institute of Mining and Metallurgical Engineers for his contributions to the petroleum industry, notably his discovery of the relation of natural gas to oil production and his pioneer advocacy of the "unit plan" of developing oil pools. He was active in the foundation of the American Petroleum Institute and long a member of its board of directors. Among his other interests was real-estate development in New York City and in Florida. He was a director of many corporations, held more than 150 patents, and was a past president of the Northwestern Electric Association, National Electric Light Association, and Ohio Gas Light Association, and also member of the American Association for the Advancement of Science, American Society of Mechanical Engineers, American Institute of Mining and Metallurgical Engineers, American Society of Heating and Ventilating Engineers, Franklin Institute, and other societies.

Edwin Wood Allen (A'03, F'22) vice-president, General Electric Company, Schenectady, N. Y., died January 1, 1940, at Johns Hopkins Hospital, Baltimore, Md. He was born at Buchanan, Va., November 9, 1879, and received the degree of bachelor of science in electrical engineering from Virginia Polytechnic Institute in 1900. The following year he entered the employ of General Electric as a student engineer at Schenactady and except for military service 1917–19 was with the company continuously until his death. He was appointed engineer of the central district in 1911 with headquarters at Chicago, Ill., in 1913 was given the additional duties of assistant manager of the district, and in 1924 became manager of the engineering department at Schenectady. He became a vice-president in 1926. During the World War he served in France as a major in the United States Army, and after the armistice went to Brussels for the War Damage Board of the Peace Commission. He had been Institute representative on the United States national committee of the International Electrotechnical Commission, and a member of the education and Lamme Medal committees, and was chairman of the latter committee at the time of his death. He was also a member of the Western Society of Engineers.

James Harvey Gravell (A'17) president, American Chemical Paint Company, Ambler, Pa., died recently, according to information just received at Institute headquarters. He was born October 12, 1880, at Philadelphia, Pa., and educated there. In 1898 he was employed by the Electrical Storage Battery Company, Philadelphia, as assistant in the electrical laboratory, and the following year went with the Ellwood Irvin Tube Works, Philadelphia, to experiment with electrical welding. In 1901 he was employed by the American Tube and Stamping Company, Bridgeport, Conn., and continued work with welding there, and later at the Baldwin Locomotive Works and in a business of which he was a partner. In 1905 he became engineer and sales agent for the Synnestvedt Automobile Company, Pittsburgh, Pa.; in 1907 assistant electrical engineer, Dodge and Day Company, Philadelphia; in 1908, laboratory assistant on special tests, Philadelphia Electric Company; in 1910 engineer in charge of electric welding, Hale and Kilburn Company, Philadelphia. In 1914 he was associated with the formation of the American Chemical Paint Company, becoming secretary-treasurer and consulting engineer. Some years later he became president of the company. He was also consulting engineer for a number of other companies, being especially concerned with welding and patents.

Stefaan Piek (A'06) retired vice-president, Niagara Hudson Power Corporation, died at Syracuse, N. Y., December 13, 1939. He

was born in The Netherlands, June 26, 1876, and was graduated as a mechanical engineer at Delft, Netherlands, in 1899 and as an electrical engineer at Zurich, Switzerland, in 1901. In the latter year he became a draftsman for Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., and was later employed by the Lackawanna Steel Company, Buffalo, N. Y., and by the Fulton Bag and Cotton Works, Atlanta, Ga. In 1904 he became electrical foreman of the Niagara Construction Company, Niagara Falls, Ont., Can., later becoming assistant engineer for the Iroquois Construction Company, and electrical engineer for the Ontario Power Company. Subsequently he became superintendent of the Niagara, Lockport, and Ontario Power Company, and later assistant general manager, general manager, and vice-president. In 1929 he was made a vice-president of the Niagara Hudson Power Corporation, and executive vice-president of the Syracuse Lighting Corporation, which was later absorbed into the Central New York Power Corporation. He retired in 1938.

Alma Preston Sessions (M'37) substation engineer, Southern California Edison Company, Ltd., Los Angeles, Calif., died recently, according to information just received at Institute headquarters. He was born April 29, 1893, at Santa Monica, Calif., and received the degree of bachelor of science in electrical engineering from the University of Arizona in 1916. During the next two years he was an instructor in science and mathematics, Gila Academy, Thatcher, Ariz., and during part of 1918 was in charge of electrical testing for the Detroit Copper Company, Morenci, Ariz. He was engaged in the design and installation of generating plants, water supply system, and other equipment at the Arizona State Industrial School, Fort Grant, from 1918 to 1922, except for short periods of testing work for the Western Machinery Diesel engine factory, Los Angeles, Calif., and the Roosevelt Power System, Phoenix, Ariz. He went to the Southern California Edison Company in 1923 as construction foreman on the Laguna Bell substation, later being transferred to the operating department. He became engineer of substations in 1926.

Omenzo George Dodge (A'93, M'95) retired commodore, United States Navy, Washington, D. C., died in June 1936, according to information just received at Institute headquarters. He was born in Mendon, Mich., June 1, 1856, and was graduated in 1877 from the United States Naval Academy. In 1880 he became an ensign and in 1887 a lieutenant in the Navy. In addition to regular duties, he served 18 months at the Smithsonian Institution, 6 months on the United States Geological Survey, and 2½ years on the United States Coast Survey. For 4 years he was an instructor in physics and chemistry at the Naval Academy, Annapolis, Md. He had various duties in the Navy as an electrical engineer, and in 1892 resigned his lieutenant's commission to become professor of mathematics, United States Navy. He attained the rank of commander in the Navy in 1899, that of captain in 1908, and subsequently reached that of commodore.

Harry Wheelock Mowry (A'18, M'29) office manager, general installation organization, Western Electric Company, New York, N. Y., died December 10, 1939, at South Orange, N. J. He was born in Cerro Gordo County, Iowa, September 12, 1881, and received the degree of bachelor of science in electrical engineering from the University of Minnesota in 1906. After a few months with the Kellogg Switchboard and Supply Company, Chicago, he joined the equipment engineering department of Western Electric at Chicago. He was placed in charge of central-office engineering at Chicago in 1917. In 1920 he became the company's resident engineer at the Automatic Electric Company's plant at Chicago, and in 1923 was appointed installation-development engineer at New York.

Harry Randall Allensworth (A'04, M'13) consulting engineer, Columbus, Ohio, died November 29, 1939. He was born January 21, 1880, at Columbus, and educated there, and through correspondence courses in technical subjects. He was employed as a telegraph operator and a wireman before becoming electrician for the City of Columbus in 1902, in which position he continued until 1914. He was valuation engineer for the Ohio State Telephone Company 1914–17, and for the Tri-State Telephone and Telegraph Company 1917–23. In 1923 he entered private practice as a consulting engineer, specializing in public-utility economics. He was also a member of the Western Society of Engineers.

Walter C. Nielsen (A'37) tester, Consolidated Edison Company of New York, Inc., New York, N. Y., died October 4, 1939, according to information recently received. He was born at New York, April 29, 1907, and received the degree of bachelor of science in electrical engineering at New York University in 1936. Since 1926 he had been employed in the test bureau of the New York Edison Company and its successor Consolidated Edison.

Membership • •

Recommended for Transfer

The board of examiners, at its meeting on January 18, 1940, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Brenton, Walter, chief engineer, Portland General Electric Company, Portland, Ore.
Nathan, E. J., engineer, The Bell Telephone Company of Pennsylvania, Philadelphia.
Work, W. R., head, department of electrical engineering, Carnegie Institute of Technology, Pittsburgh, Pa.

3 to Grade of Fellow

To Grade of Member

Jahn, Emil, electrical design engineer, J. G. White Engineering Corporation, New York, N. Y.
Macfarlane, G. O., manager, General Electric Company, Memphis, Tenn.
Patterson, H. M., electrical engineer, Copper Wire Engineering Association, Washington, D. C.
Strong, E. M., assistant professor of electrical engineering, Cornell University, Ithaca, N. Y.

4 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geographical Districts. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before February 29, 1940, or April 30, 1940, if the applicant resides outside of the United States or Canada.

United States and Canada

1. NORTH EASTERN

Ahern, W. R., New England Power Company, Quincy, Mass.
Bokan, J. J., General Electric Company, Schenectady, N. Y.
Boyer, R. P., Jr., 125 Franklin Street, Newton, Mass.
Buckley, T. F., Central New York Power Corporation, Syracuse, N. Y.
Cepelak, J., Jr., Scovill Manufacturing Company, Waterbury, Conn.
Dimock, W. B., Stamford Gas and Electric Company, Stamford, Conn.
Dutton, J. C., General Electric Company, Pittsfield, Mass.
Franklin, J. S., General Electric Company, West Lynn, Mass.
Gauss, F. S., Palmer Electric and Manufacturing Company, Wakefield, Mass.
Hoare, D. L., The Southern New England Telephone Company, New Haven, Conn.
Hughson, J. D., General Railway Signal Company, Rochester, N. Y.
James, A. A., Southern New England Telephone Company, New Haven, Conn.
McCurry, R. T., General Electric Company, Pittsfield, Mass.
Mikelson, W., General Electric Company, Schenectady, N. Y.
Packard, L. E., General Radio Company, Cambridge, Mass.
Rissberger, A. C., Jr., 160 Rugby Avenue, Rochester, N. Y.
Rosenthal, I., Club Photo Service, Boston, Mass.
Rousault, C. L., General Electric Company, Lynn, Mass.
Segerstrom, C. A., Jr., Hygrade Sylvania Corporation, Salem, Mass.
Smith, R. J. (Member), Palmer Electric and Manufacturing Company, Wakefield, Mass.
Sprague, R. C. (Member), Sprague Specialties Company, North Adams, Mass.
Sweeny, J. O., General Electric Company, Pittsfield, Mass.
Williams, C. A. (Member), The United Illuminating Company, New Haven, Conn.

2. MIDDLE EASTERN

Adolphe, M. H., Owens-Corning Fiberglas Corporation, Newark, Ohio.
Armor, M. K., Rural Electrification Administration, Washington, D. C.
Ball, H. E., Cutler Hammer, Inc., Cleveland, Ohio.
Barkle, J. E., Jr., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Barr, T. L., Federal Works Agency, Washington, D. C.
Beckett, J. C., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Black, C. F., Republic Steel Corporation, Cleveland, Ohio.
Boone, E. M., Ohio State University, Columbus.
Cachat, J. F., Cleveland Electric Illuminating Company, Cleveland, Ohio.
Clark, J. J., Jr., Westinghouse Electric and Manufacturing Company, Pittsburgh, Pa.
Costrell, L., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Crummitt, C. B., Chesapeake and Potomac Telephone Company, Washington, D. C.
Cushing, G. B., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Dornbush, H. W., Pennsylvania Transformer Company, Pittsburgh.
Edwards, P. J., Westinghouse Electric and Manufacturing Company, Sharon, Pa.
Risen, N., Westinghouse Electric and Manufacturing Company, Philadelphia, Pa.
Ellis, W. R., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Eyman, D. H., Westinghouse Electric and Manufacturing Company, Sharon, Pa.

Fallon, G. P. (Member), Consolidated Gas, Electric Light and Power Company of Baltimore, Baltimore, Md.
Ford, J. H., Allis-Chalmers Manufacturing Company, Washington, D. C.
Gall, C. R., B. A. Wesche Electric Company, Cincinnati, Ohio.
Gehrung, J. H., Republic Steel Corporation, Cleveland, Ohio.
Gray, F. C. (Member), Copper Wire Engineering Association, Washington, D. C.
Holland, C. W., Jr., American Car and Foundry Company, Berwick, Pa.
Hopkins, R. B., General Electric Company, Philadelphia, Pa.
Howard, L. E., General Electric Company, Philadelphia, Pa.
Jensen, I., Pusey and Jones Corporation, Wilmington, Del.
Johnstone, B. B., Rural Electrification Administration, Washington, D. C.
Kandoian, A. G., International Telephone Development Company, Newark, N. J.
Kussmaul, R. E., Public Service Electric and Gas Company, Newark, N. J.
Leet, C. H., Electric Storage Battery Company, Pittsburgh, Pa.
Manwaring, A. H., II (Member), Philadelphia Electrical and Manufacturing Company, Philadelphia, Pa.
McKay, J. L. (Member), Bell Telephone Company of Pennsylvania, Philadelphia.
Mikos, J. J., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Mills, R. W., Cleveland Electric Illuminating Company, Cleveland, Ohio.
Nau, R. H., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Nooe, H. R., Jr., Rural Electrification Administration, Washington, D. C.
Nopper, E. J., Sun Oil Company, Philadelphia, Pa.
O'Connor, J. J., Consolidated Gas, Electric Light and Power Company, Baltimore, Md.
Pollard, C. L., Pennsylvania Power and Light Company, Danville.
Ray, J. J., Philadelphia Electric Company, Philadelphia, Pa.
Riley, J. J., Delco Products, Dayton, Ohio.
Sauerwein, G. F., Jr., Westinghouse Lamp Company, Trenton, N. J.
Smith, S. S., Jr., Duquesne Light Company, Pittsburgh, Pa.
Smith, W. T., Rural Electrification Administration, Washington, D. C.
Snedeker, M. L., United Broadcasting Company, Cleveland, Ohio.
Sparrow, W. G., Bell Telephone Company of Pennsylvania, Sharon.
Stage, H. O., Carlton Lamp Corporation, Union City, N. J.
Taylor, G. H., Eclipse Aviation Company, Bendix, N. J.
Toshniwal, B. D., RCA Manufacturing Company, Inc., Camden, N. J.
Walz, H. G., Public Service Electric and Gas Company, Jersey City, N. J.
Wilkinson, R. W., Bell Telephone Company of Pennsylvania, Philadelphia.
Yevick, J. G., Potomac Electric Power Company, Washington, D. C.
Zehfuss, E. A. (Member), Duquesne Light Company, Pittsburgh, Pa.

3. New York City

Bernius, W. K., Sperry Gyroscope Company, Brooklyn, N. Y.
Boyd, J. (Member), Westinghouse Electric and Manufacturing Company, New York, N. Y.
Clasen, A. J., American Bank Note Company, New York, N. Y.
Del Papa, F., National Sugar Refining Company, Long Island City, N. Y.
Ferguson, J. R. (Member), New York Telephone Company, New York, N. Y.
Fickinger, C. H., New York Telephone Company, New York, N. Y.
Finch, T. R., Bell Telephone Laboratories, Inc., New York, N. Y.
Fulton, R. A., Jr., Cheney and Foster, New York, N. Y.
Gardner, M. L., Westinghouse Electric and Manufacturing Company, New York, N. Y.
Hammel, A. P. (Member), New York Telephone Company, New York, N. Y.
Hilbert, E. A., Consolidated Edison Company of New York, Inc., New York, N. Y.
Hodges, E. P., New York Telephone Company, New York, N. Y.
Hooker, H. H., Underwriters' Laboratories, Inc., New York, N. Y.
Johnson, L. W. (Member), c/o Robert Goelet, New York, N. Y.
Kerner, J. R., Westinghouse Electric and Manufacturing Company, New York, N. Y.
Kolisz, P. P., Bell Telephone Laboratories, Inc., New York, N. Y.
Noller, W. E., Bell Telephone Laboratories, Inc., New York, N. Y.
Reveal, P. A., WOR and The Mutual Broadcasting System, New York, N. Y.
Robisch, I. C., Consolidated Edison Company of New York, Inc., New York, N. Y.
Samoos, W. J., Stanroy Management Corporation, New York, N. Y.
Smith, H. M., Columbia University, New York, N. Y.
Smoot, A. W., Underwriters' Laboratories, Inc., New York, N. Y.
Tannenbaum, A. (Member), Consolidated Edison Company of New York, Inc., New York, N. Y.
Van Nort, L. N., New York Telephone Company, New York, N. Y.
Verdi, J. J., Brooklyn Edison Company, Inc., Brooklyn, N. Y.
Volp, L. J., Consolidated Edison Company of New York, Inc., New York, N. Y.
von der Horst, W., Jr., Aetna Insurance Company, New York, N. Y.

4. Southern

Bostwick W. M., Florida Power and Light Company, Daytona Beach.
Flynt, E. R., Alabama Power Company, Huntsville.
Harry, H. E., War Department, Second District, New Orleans, La.
Horney, H. W., Carolina Aluminum Company, Badin, N. C.
Hutchison, C. B., Westinghouse Electric and Manufacturing Company, Memphis, Tenn.
Kanning, R. H., Alabama Power Company, Mobile.
Kraybill, R. K., Duke University, Durham, N. C.
Levkoff, M., 521 Santee Avenue, Columbia, S. C.
Lewis, C. P., Sandlick Coal Company, Whitesburg, Ky.
Markham, R. T., Gibson County Membership Corporation, Trenton, Tenn.
Ray, C. A., Southern Bell Telephone and Telegraph Company, Knoxville, Tenn.
Reed, C. E., Lyman C. Reed, New Orleans, La.
Scott, M. F. (Member) Alabama Power Company, Birmingham.
Tatum, G. M., Virginia Public Service Company, Charlottesville.
Walker, C. S., University of Alabama, University, Ala.
Woolfolk, J. K. (Member), State Corporation Commission of Virginia, Richmond.

5. Great Lakes

Anderson, R. L., American Gas and Electric Service Corporation, Muncie, Ind.
Beattie, C. S. (Member), Delta-Star Electric Company, Chicago, Ill.
Boeker, E. T., General Electric X-ray Corporation, Chicago, Ill.
Cragg, R. E., Commonwealth Edison Company, Chicago, Ill.
Dollenmaier, J. M., Line Material Company, Detroit, Mich.
Ewy, A., Milwaukee, Wis.
Feldhausen, C. P. (Member), Cutler Hammer, Inc., Milwaukee, Wis.
Gregory, J., Guardian Electric Manufacturing Company, Chicago, Ill.
Guldi, W. E., Carnegie-Illinois Steel Corporation, Gary, Ind.
Hansen, K. H., Cutler Hammer, Inc., Milwaukee, Wis.
Hausske, G. A. (Member), Pure Oil Company, Chicago, Ill.
Jones, E. E., Iowa State College, Ames.
Karle, R. D., American Telephone and Telegraph Company, Chicago, Ill.
Koehler, A. A., Public Service Company of Indiana, Indianapolis.
Kryder, P. A., Allis-Chalmers Manufacturing Company, Milwaukee, Wis.
Ku, T. H., 471 North Grant Street, West Lafayette, Ind.
Lee, S., 208 South Street, West Lafayette, Ind.
Lyon, W. D., Illinois Bell Telephone Company, Chicago.
Marcus, J. L., American Electric Company, Indianapolis, Ind.
May, R. F., University of Michigan, Ann Arbor.
Michaels, H. J., Allis-Chalmers Manufacturing Company, West Allis, Wis.
Mikolic, C. R., Allis-Chalmers Manufacturing Company, West Allis, Wis.
Miller, R. E., Allis-Chalmers Manufacturing Company, Milwaukee, Wis.
Mirick, R. B., Pillsbury Flour Mills Company, Minneapolis, Minn.
Polakowski, E. J., Cutler Hammer Inc., Milwaukee, Wis.
Rosch, J. M., Commonwealth Edison Company, Chicago, Ill.
Ruth, J. A., University of Michigan, Ann Arbor.
Saunders, R. M., University of Minnesota, Minneapolis.
Schaefer, M. W., Allis-Chalmers Manufacturing Company, West Allis, Wis.
Senn, J. A., Cutler Hammer Inc., Milwaukee, Wis.
Snyder, V. J., General Electric Company, Detroit, Mich.
Sorflaten, C. G., Commonwealth Edison Company, Chicago, Ill.
Thomas, H. A., Purdue University, West Lafayette, Ind.
Thomen, M. K., Jr., General Electric Company, Fort Wayne, Ind.
Yonkers, E. H., Joslyn Manufacturing and Supply Company, Chicago, Ill.

6. North Central

Mueller, J. W., Nebraska Power Company, Omaha, Nebr.
Pirtle, P. R., Box 744, Green River, Wyo.
Steen, W. J., Nebraska Power Company, Omaha.
Weers, A. F., Rocky Mountain Engineering Company, Denver, Colo.

7. South West

Brinker, C. S., Westinghouse Electric and Manufacturing Company, St. Louis, Mo.
Burns, C. H., Phillips Petroleum Company, Bartlesville, Okla.
Davis, S. W. (Member), Southwestern Public Service Company, Amarillo, Tex.
Esheiman, H. K., Kansas Power Company, Liberal.
Francis, M. C., Southwestern Bell Telephone Company, Kansas City, Mo.
McReynolds, J. M., Houston Lighting and Power Company, Houston, Tex.
Morris, W. C., Jr., Southwestern Gas and Electric Company, Overton, Tex.
Petzing, W. N., General Electric Company, Dallas, Tex.
Philpott, C. G., Missouri Power and Light Company, Jefferson City.
Price, J. T., Southwestern Public Service Company, Amarillo, Tex.
Rivoire, O. G., Dallas Power and Light Company, Dallas, Tex.
Robson, R., Union Electric Company of Missouri, Webster Groves.
Seewald, L., Southwestern Public Service Company, Amarillo, Tex.
Setzer, L. E., Huzak Route, Box 15, Steelville, Mo.
Skinner, R. S., Southwestern Bell Telephone Company, Kansas City, Mo.
Tosch, R. L., Dallas Power and Light Company, Dallas, Tex.
Totten, R. E., Clifton, Kans.
White, H. A., General Electric Company, Dallas, Tex.
Wightman, F. N., Westinghouse Electric and Manufacturing Company, St. Louis, Mo.
Wills, E. E., Westinghouse Electric and Manufacturing Company, St. Louis, Mo.
Wood, F. P., Dallas Power and Light Company Dallas, Tex.
Woods, H. S., General Electric Company, Kansas City, Mo.

8. Pacific

Cummings, C. C., Bank of America, San Diego, Calif.
English, A. M., 462 Stow Avenue, Oakland, Calif.
Glavinovich, L. V., Pacific Gas and Electric Company, San Francisco, Calif.
Gould, E. H., Jr. (Member), 927½ Carolina Street, Vallejo, Calif.
Gow, K. P., U. S. Soil Conservation Service, Los Angeles, Calif.
Lipow, J. H., 2908 West Vernon Avenue, Los Angeles, Calif.
Matthew, T., Southern California Edison Company, Santa Monica, Calif.
Sumerlin, W. T., Hollywood Transformer Company, Hollywood, Calif.
Thompson, J. L. (Member), Kelman Electric and Manufacturing Company, Los Angeles, Calif.
Troost, T. W. (Member), Imperial Irrigation District, Imperial, Calif.
Von Bergen, C. A., Pacific Gas and Electric Company, Oakland, Calif.
Whitney, G. W., Simmons Company, San Francisco, Calif.
Wynn, H. L., Pacific Electrical Manufacturing Corporation, San Francisco, Calif.

9. North West

Bailey, B. M., Pacific Power and Light Company, Portland, Ore.
Embry, A. L., Board of Fire Underwriters of the Pacific, Salt Lake City, Utah.
Gibney, E. L. (Member), City of Seattle, Seattle, Wash.
Martin, E. E., W. S. McCren, Jr., and R. M. Towne, Engineers, Tacoma, Wash.
Schneider, H. R., Montana Power Company, Great Falls.
Swanson, L. W., United States Engineers, Portland, Ore.
Treffinger, F. M., Puget Sound Power and Light Company, Seattle, Wash.
Walker, R. K., University of Washington, Seattle.
Washburn, C. A., Utah Power and Light Company, Grace, Idaho.

10. Canada

Ackhurst, W. H., Canadian General Electric Company, Ltd., Peterboro, Ont.
Findlay, S. M., Station CFGP, Grande Prairie, Alberta.
Larsen, M. P., British Columbia Underwriters Association, Vancouver.
Mouil, W. C., Canadian General Electric Company, Ltd., Peterboro, Ont.

Total, United States and Canada, 207

Elsewhere

Bourlon, A., Hubard and Bourlon Sucrs., Mexico, D. F., Mexico.
Havinga, M. J. S., c/o Municipality, Wolmaranstad, Transvaal, South Africa.
Lewis, D. G., Cia de Electricidad del Sud Argentino, Buenos Aires, Argentine, S. A.
Shah, S. M. H., Shkoor Ali and Sons, Simla, Punjab, India.

Total elsewhere, 4

Transactions
Preprint of Papers and Discussions Comprising Pages 65–128 of the 1940 Volume

Capacitor Relay Timing in Industrial Control

CARROLL STANSBURY
FELLOW AIEE

THEO. B. JOCHEM
ASSOCIATE AIEE

Synopsis: The trend toward electrical means of providing timing for motor control is evidenced in the use of capacitor-timed relays and contactors. Though employed for some time in welding applications, the advent of capacitor timing in the motor control field is fairly recent. The general analytical considerations are presented, followed by a discussion of the component parts of the timer. Some attention is paid to limitations, particularly in regard to the effect of line voltage fluctuations.

THE provision of simple, reliable, and inexpensive timing means has been a perennial problem with industrial-control engineers. Many different physical phenomena involving time have been made to serve as the basis of timing systems, with varying success. During this process of development, the accepted method of motor acceleration has passed through an earlier stage in which current- or voltage-responsive methods were in favor, to that of more recent practice which consists of carrying out the various steps of armature and field acceleration in accordance with a definite time sequence. Thus, the development of timing methods has been accelerated by their increasing importance in the field of motor control.

Moreover, the recent rapid development of the resistance-welding field has presented to control engineers timing problems of a very exacting nature, and has resulted in refinement of existing methods and the introduction of new ones. These methods are now being carried over into the older domains of industrial control with beneficial results.

The earlier forms of timing employed in motor acceleration were mostly of mechanical type, such as dashpot and clockwork mechanisms. More recently, however, the trend has been toward what may be termed electrical means, based on the storage of energy in self-inductance elements or in capacitors. The former type has been in successful use for a number of years (in the so-called "inductive time limit" or "magnetic time" controllers).[1]

On the other hand, though long viewed as a hopeful possibility, capacitor timers have presented many difficult problems only recently overcome in such a manner as to make their use entirely practical. Recent improvements in electrolytic capacitors, particularly those of the etched-plate and fabricated-plate types, have aided in solving such problems, and at least one manufacturer of industrial control is already employing capacitor timing quite extensively both in resistance welding[2] and in motor control. It is the purpose of this paper to outline the general principles of this type of control, and to describe some typical applications.

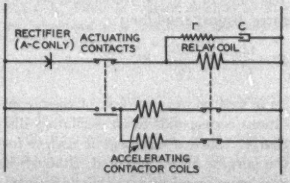


Figure 1. A circuit for timing two accelerating contactors employing a capacitor timing relay having two independent armatures

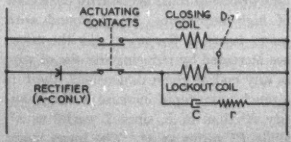


Figure 2. Capacitor timing circuit suitable for lockout-type accelerating contactor

Typical Capacitor-Timing Circuit

The earliest capacitor timers in general use were those employing paper capacitors of about one-microfarad capacity in conjunction with rheostat having resistance on the order of one megohm. This timing combination was connected in the grid circuit of a vacuum or gas triode which acted as an amplifier and controlled power switching apparatus of either magnetic or electronic type. Such "capacitor-resistor" timers have been widely used in resistance-welding control and elsewhere.

However, for motor-acceleration timing and many other purposes this arrangement is too complicated to be practical, particularly in the typical case where two or more successive timing periods are involved. The necessity for periodic replacement of tubes has been an additional barrier.

In an attempt to overcome these disadvantages, it has been found possible to simplify the capacitor-resistor idea by the employment of capacitors of much larger capacity (on the order of 25 microfarads) making possible the elimination of the amplifying tube. Also, to meet the need for multiple timing, relays have been developed which provide two or more independently adjustable time periods with a single magnetic structure.

The circuit used for this purpose is extremely simple (figure 1). The timing-relay coil is connected in parallel with a capacitor and has two or more independent armatures which are connected in circuit with coils of accelerating contactors. When the actuating contacts are in the position shown, the capacitor is charged and the relay coil is energized. When the actuating contacts are moved into the other position, the coil and capacitor are cut off from the line, and the relay armatures drop in turn after definite time intervals.

Variations of this simple scheme are obviously possible, such as connection of the relay coil in series with the capacitor in a charging circuit. However, the ap-

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CARROLL STANSBURY is development engineer and THEO. B. JOCHEM is experimental engineer, Cutler-Hammer, Inc., Milwaukee, Wis.

1. For all numbered references, see list at end of paper.

parently inevitable, though small, leakage current in electrolytic capacitors prevents ultimate reduction of current to zero in a charging circuit and makes the shunt discharge arrangement shown the more desirable.

It is also possible to use the delayed-release magnet as a lockout or restraining

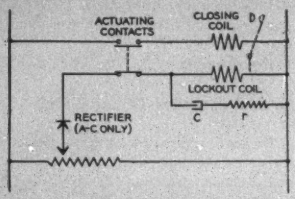

Figure 3. Same as figure 2 except for adjustment of timing by varying initial ampere-turns

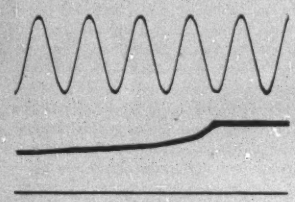

Figure 4. Variation of coil current at start of timing period

Upper trace is 60-cycle timing wave. Ohms in resistor r equal twice ohms in coil

magnet in relays or contactors having a separate closing coil (figure 2).

This arrangement has the distinct advantage that the delayed-release coil can be designed for most efficient delay exclusively, whereas in the scheme of figure 1 this magnet has also to perform the function of pulling in the relay. Both figures 1 and 2 are being used, but the former more extensively because it permits using a single standardized timing relay with a wide variety of contactors of standard type, both direct current and alternating current. When used on alternating current it is merely necessary to add the half-wave rectifier unit indicated on the figures.

Nature of Timing Transients

The capacitor-relay timer differs from the electronic timers in that the discharge path contains self-inductance as well as resistance. It is shown further on in this paper that the former may be neglected in most practical cases, but for purposes of analysis it is necessary to take self-inductance into account initially. This involves the well-known transient relationships in a series L-C-R circuit[3] which are repeated here only insofar as they clarify the points under discussion.

Let

L = self-inductance of coil, henries
R = resistance of coil (plus external resistor if used), ohms
C = capacity, farads
i = transient current, amperes
i_0 = initial transient current, amperes
ϵ = 2.718
t = time, seconds
A_1 and A_2 = integration constants
$B = \sqrt{R^2 - 4L/C}$
E = line volts = initial volts on charged capacitor
n = turns in coil
m = ampere-turns at which magnet releases armature

The fundamental equation is

$$L\frac{d^2i}{dt^2} + R\frac{di}{dt} + \frac{i}{C} = 0 \qquad (1)$$

and is applicable to either charging or discharging conditions. For the present purpose, however, the discharging condition is the one of practical importance and is the only one considered here. The general solution of equation 1 is

$$i = A_1\epsilon^{\frac{-R+B}{2L}t} + A_2\epsilon^{\frac{-R-B}{2L}t} \qquad (2)$$

Applying the terminal conditions $i = 0$, capacitor volts $= E$, when $t = 0$, to equation 2 results in the equation:

$$i = \frac{E}{B}\left[\epsilon^{\frac{-R+B}{2L}t} - \epsilon^{\frac{-R-B}{2L}t}\right] \qquad (3)$$

The value of B in the exponential permits three distinct conditions:

$$R^2 < \frac{4L}{C}, \quad R^2 = \frac{4L}{C}, \quad R^2 > \frac{4L}{C}$$

As is well known, the first of these conditions corresponds to an oscillatory discharge. Such a discharge is useless for the purpose here considered, although it does have practical applications in magnet operation in the so-called *impulse* operation of magnetic contactors.[4]

Delayed-release magnets of the type here discussed must necessarily have coils of high impedance, being wound with many turns of fine wire. As the turns are increased by reducing the size of wire in any coil of given dimensions, there is a much more rapid increase in the quantity R^2 than in L, since L varies as n^2, while R^2 varies as n^4. The lower space factor of finer wire accentuates this condition. Furthermore, the values of capacity involved are large (on the order of 25 microfarads).

From the above facts it follows that the normal condition in the present application is that $R^2 > 4L/C$. In practical cases of coils and capacitors used for timing of this type, R^2 varies from 2 to 2.5 times $4L/C$. Calculation of timing under such conditions which neglect L altogether are found to give results within the limits of accuracy established by the normal manufacturing variations of the circuit components.

Where L is neglected, equation 3 reduces to:

$$i = i_0\epsilon^{\frac{-t}{CR}} = \frac{E}{R}\epsilon^{\frac{-t}{CR}} \qquad (4)$$

which is solved for t as follows:

$$t = CR\ \log_\epsilon \frac{i_0}{i} \qquad (5)$$

These are the equations applicable to the simple capacitor-resistor timer of discharge type.

In a practical capacitor-relay timer, the timing magnet will release at some definite value of ampere-turns, which can be introduced into equation 5 by writing it:

$$t = CR\ \log_\epsilon \frac{ni_0}{mi} \qquad (6)$$

Methods of Adjustment

Questions of relay and coil design and selection of circuit constants are to some extent dependent on the method adopted for providing adjustment of timing. The available methods are implicitly expressed in equation 6.

Type 1—Adjustment of Capacity. Practicability of this method suffers from the

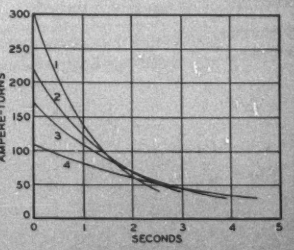

Figure 5. Ampere-turns versus time for different values of external resistance r

Curve 1—r = 30,000 ohms
Curve 2—r = 50,000 ohms
Curve 3—r = 70,000 ohms
Curve 4—r = 122,000 ohms
Coil resistance = 20,000 ohms

lack of adjustable capacitors of large capacity. It is, however, being used on resistance welding timers where the limited timing range makes stepped adjustment of capacity (by a fan switch) permissible. Adjustment by capacity has the advantage that it permits the use of an insulated dial with definitely calibrated points.

Type 2—Adjustment of Resistance. This method is not practicable because there is no way to adjust the resistance of the relay coil.

Type 3—Adjustment of Initial Ampere-Turns. This may be done by varying the voltage to which the capacitor is charged. Without unreasonable circuit complication it is only applicable where the delayed-release magnet has only a restraining function, as in figure 2. Figure 3 shows a practical circuit, which, however, is not in use because of the greater simplicity of other methods.

Type 4—Adjustment of Dropping Ampere-Turns. To accomplish this simplest method of adjustment it is only necessary to provide for changing the magnetic gap of the relay armature when in closed position. It is applicable where the delayed-release magnet has both a pickup and restraining function (figure 1) as well as where it has a restraining function only (figure 2).

Factors Affecting Timing

In all cases it is desirable to use a resistor unit r in series with the capacitor. The ohmic value of this resistor may be anything from a minimum value which is recommended for protecting the capacitor against surges, to a much higher value which may be desirable to obtain maximum timing efficiency. Whether the latter may be used depends upon whether it is permissible to take appreciable time to recharge the capacitor between operations. In some cases, additional actuating contacts are used to commutate this

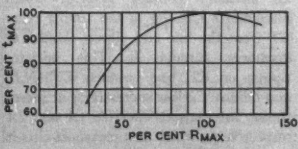

Figure 6. Plot of equation 10

resistor so that its ohmic value is low for the charging condition and high for the discharging condition.

Referring to figure 1, it will be seen that the ampere-turns in the relay coil, before the actuating contact is opened, are simply determined by the coil characteristics and the line voltage. When the actuating contact is opened, the current in the relay coil drops in a transient period of negligible duration to a value depending upon the initial charge on the capacitor and the resistance in circuit, figure 4. Thereafter the current varies substantially in accordance with equation 4.

Where the magnet has a pickup as well as a holding function, the coil design is determined by the former. Where the function is holding only, on the other hand, the coil is wound with the finest wire which can be wound economically. Figure 5 is a set of curves plotted in accordance with equation 4, for a particular coil and capacitor and for various values of R. These curves are plotted in ampere-turns rather than amperes because

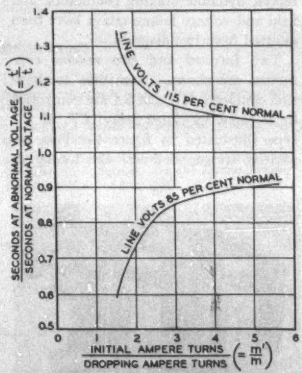

Figure 7. Effect of voltage variation on timing, expressed as a function of the ratio of initial to final ampere-turns

the pickup and dropping characteristics of relays are so expressed.

To determine the value of R which results in maximum timing, the form of equation 6 may be changed to

$$t = CR \log_e \frac{En}{mR} \tag{7}$$

wherein m is the dropping ampere-turns.

Differentiating equation 7, and equating to zero to find R for maximum t, results in

$$R_{max} = \frac{En}{me} \tag{8}$$

$$t_{max} = CR_{max} \tag{9}$$

There are two practical considerations

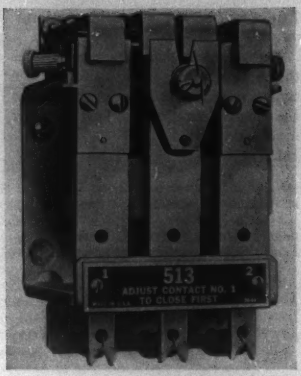

Figure 8. The relay for armature acceleration has two (outer) armatures for timing, and a third (center) armature for insuring correct operating sequence

which make it undesirable to use the full value of total resistance indicated by equation 8:

1. Variation of coil ampere-turns near the point of relay armature release may be so gradual that small changes in release ampere-turns cause appreciable changes in timing.

2. Effect of line-voltage fluctuations on the timing is excessive. This factor is discussed in the next section of this paper.

Combining equations 7, 8, and 9 results in the following equation which expresses the effect on the timing of using a value of R which differs from R_{max}:

$$\frac{t}{t_{max}} = \frac{R}{R_{max}} \log_e \frac{R_{max}\epsilon}{R} \tag{10}$$

This equation is plotted in figure 6 and shows that reduction of R to 50 per cent of R_{max} only results in 15 per cent reduction in timing. This value of R corresponds approximately to that used in actual practice. Where the timing adjustment is by variation of closed magnetic gap (type 4) the value of R is important not only for its effect in increasing the time periods available with given apparatus, but also because the flatness of the timing curve determines the range of timing adjustment available. Thus with curve 3 of figure 5 the range of timing from zero to four seconds is obtainable by changing the dropping ampere-turns from 170 to 35, whereas to obtain the same range of adjustment under the conditions of curve 1, figure 5, may be seen to require a much wider adjustment of dropping ampere-turns, which may not be obtainable in practice.

Effect of Line-Voltage Fluctuations

Fluctuation in line voltage constitutes the most serious adverse factor in this timing method. It is desirable to show the extent of its effect and how the latter may be minimized.

Let

m = dropping ampere-turns, as above
m' = initial ampere-turns, at nominal line volts
k = ratio of actual to nominal line volts
t and t' = timing at nominal and actual line volts, respectively

Then equation 6 may be written:

$$t = CR \log_e \frac{m'}{m} \tag{11}$$

and, since initial ampere-turns is proportional to line volts,

$$t' = CR \log_e \frac{km'}{m}$$

or

$$\frac{t'}{t} = \frac{\log_e \frac{km'}{m}}{\log_e \frac{m'}{m}} \tag{12}$$

In figure 7, equation 12 is plotted for $k = 0.85$ and 1.15. These curves clearly show that low values of m'/m accentuate the effect of line voltage fluctuations. If $R = R_{max}$ is used in order to obtain maximum timing, the initial ampere-turns are, using equation 8,

$$m' = \frac{En}{R_{max}} = m\epsilon \text{ or}$$

$$\frac{m'}{m} = \epsilon = 2.718$$

It was stated in the preceding section that use of the full value of R_{max} leads to excessive sensitivity to line voltage fluctuations. Reference to figure 7 shows a variation of roughly ±15 per cent in time for a ±15 per cent voltage variation, which might be permissible. But in the case of a type 4 adjustment, timing is reduced by increasing the dropping ampere-turns; that is, by increasing m in equation 11, with corresponding decrease in m'/m. Figure 7 shows that decreases in m'/m by this method below 2.718 over any appreciable range would result in very excessive voltage sensitivity over the lower end of the range.

On the other hand, by using considerably lower values of R, such as $R_{max}/2$, this tendency is greatly reduced since, for maximum timing, $m'/m = 5.43$. An inspection of figure 7 shows that the permissible range of variation of m'/m in this case is considerably greater than when $R = R_{max}$. Experience has shown this to be an acceptable compromise value.

Typical Controller

Figure 8 illustrates a capacitor-timed relay generally used for armature acceleration. The outside armatures are provided with normally closed contacts and individual closed magnetic gap adjustments for timing. A center armature carries a normally open contact and a fixed closed magnetic gap. Figure 9 shows a similar relay with two independently timed armatures carrying normally open contacts. This relay finds particular use in field acceleration.

A typical automatic d-c motor control with both armature and field acceleration is shown in figure 10. Figure 11 is the elementary diagram for this control. For the sake of simplicity, the overload relays, dynamic braking contactors, and field and voltage failure relays have been omitted from this diagram.

Two forward and two reverse contactors are shown. Armature acceleration contactors 1*A* and 2*A* are controlled by a capacitor-timed relay, *CT*, of the type illustrated in figure 8. Two capacitors are supplied with this timing relay in reversing controllers of this type, for reasons outlined below. The capacitors are designated *CAP.*-1 and *CAP.*-2 on the diagram and are connected in the circuit with normally closed auxiliary contacts on the reversing contactors, as indicated. A capacitor relay, *FA*, identical with that shown in figure 9, provides field acceleration.

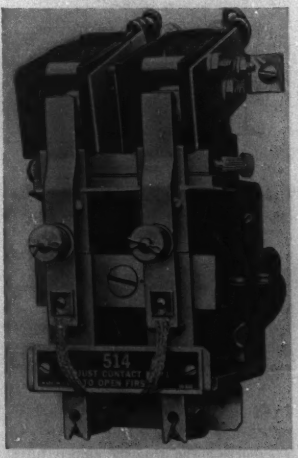

Figure 9. The relay for field acceleration has two independently timed armatures

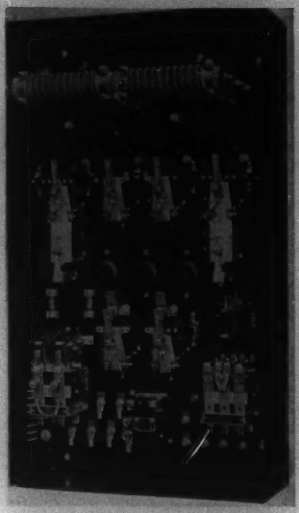

Figure 10. A full-reverse nonplugging, dynamic-braking d-c motor control with three steps of armature and two steps of field acceleration

Operation of this control is, briefly, as follows. With voltage on lines L_1 and L_2, relay *CT* picks up, closing contact *CT-N.O.* and opening contacts CT_1-*N.C.* and CT_2-*N.C.* Capacitors, *CAP.*-1, *CAP.*-2, and *CAP.*-3 are charged through their respective external resistors. Relay *FA* also operates, closing contacts FA_1 and FA_2.

When the "forward" push button is closed contactors 1*F* and 2*F* close, connecting the motor armature to the line through the two steps of starting resistance. Contactor 1*F*, in closing, opens an auxiliary contact 1*F-N.C.* which disconnects the coil of the timing relay *CT* from the line and allows *CAP.*-2 to discharge through it. This initiates timing on *CT*, and contacts *CT*1-*N.C.* and *CT*2-*N.C.* close successively at preset timing intervals to energize 1*A* and 2*A* respectively, which in turn short-circuit the two steps of starting resistance. During this time, contact *CT-N.O.* has opened and the main contactors 1*F* and 2*F* are maintained through the interlocking resistance. Contactors 1*F* and 2*F* are picked up only when contact *CT-N.O.* is closed. The latter is operated by the center relay armature which is provided

with a larger open magnetic gap than the armatures carrying contacts *CT1-N.C.* and *CT2-N.C.* This assures that the latter two contacts are opened before contactors 1*F* and 2*F* close. Contactors 1*A* and 2*A* cannot therefore close at the same time as 1*F* and 2*F* and connect the motor armature directly across the line.

When contactor 2*A* closes, it operates an auxiliary contact 2*A-N.C.* which disconnects relay *FA* from the line and allows *CAP.*-3 to discharge through the coil. Contacts *FA*1 and *FA*2 open successively at preset intervals inserting resistance in series with the motor shunt field. The rheostat permits manual control of the motor speed.

As shown on the diagram, two capacitors are used in conjunction with the relay coil *CT*. While operating in the forward direction *CAP.*-2 discharges through coil *CT* to provide timing. On reversal, the auxiliary contact 2*R-N.C.* opens and allows *CAP.*-1 to discharge through coil *CT*. An alternate circuit utilizing a single capacitor is designated by the broken line on the diagram. Because of the series resistor, a definite time interval is required to charge the capacitor to line voltage. When the "reverse" button is pressed immediately after the motor has stopped from "forward" operation, sufficient time might not be available for a complete charge of the single capacitor. This would result in shorter timing of contactors 1*A* and 2*A*, and a too rapid acceleration of the motor. To protect against this possibility, a capacitor is provided for each direction of rotation of the motor. While it is operating in one direction, the capacitor circuit controlling timing in the reverse direction remains across the line and is charged to full line voltage.

Conclusion

Although the development described in the foregoing paper is quite recent, several hundred controllers employing capacitor-relay timing for acceleration are already in successful service in varied applications. The inherent advantages of this method, as compared with earlier methods, appear to justify the belief that it will be used very extensively in the future.

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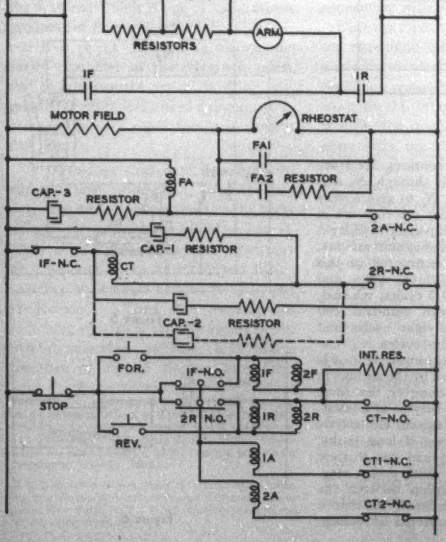

Figure 11. An elementary diagram of connections for the controller illustrated in figure 10

Discussion

F. H. Winter (nonmember) and **L. T. Rader** (both of General Electric Company, Schenectady, N. Y.): We agree with Messrs. Stansbury and Jochem that accurate means for obtaining various time intervals is a very important part of industrial-control work; and the use of capacitors for this purpose offers a very flexible and accurate method of control. In applications where dirt may interfere with operation, operators object to small mechanical arrangements such as escapements, dashpots, and motors to obtain time delays. One of the standard devices having no moving parts but using electrical induction is the coil with short-circuited secondary or copper jacket. It has, however, the two limitations of:

1. A maximum time delay drop-out of seven or eight seconds.
2. It does not lend itself to easy adjustment during operation.

Therefore, as stated by the authors, the comparatively recent reduction in cost of manufacture and decrease in sizes of capacitors, as well as the demand for longer time intervals and more flexible control, has intensified their application. In circuits using no electronic devices we have obtained ranges in time from seven cycles to three minutes. The latter figure was obtained on a motor-starter using 600 microfarads at 250 volts.

We should like to show several uses of capacitor circuits other than those presented. These are:

1. Compensation for voltage changes.
2. A high pickup force.
3. A fast pickup and fast drop-out.
4. Time delay pickup.
5. Use of capacitors as interlocks.

Figure 7 in the authors' paper shows the effect on timing of line voltage fluctuation. Where good accuracy is required, we have eliminated this variation in timing with variation in voltage by the use of the circuit shown in figure 1 of this discussion.

A compensating coil is in series with a regulating rheostat across a potentiometer so that its ampere-turns are directly proportional to the line voltage and in opposition to those of the main coil. When the master control switch (*MCS*) is closed, the normally open interlock completes the circuit to the potentiometer connection, thus energizing the compensating coil. Meantime, the second *N.O.* contact on the master control switch has allowed the capacitor to become rapidly charged from the line through only a small limit resistance. The device picks up and opens the *N.C.* interlock, thus inserting the discharge resistance which will give the proper time constant. To start the time-out operation, the master-control-switch contacts are opened, disconnecting the main coil from the 250-volt bus and putting it across the capacity and discharge resistor in series. The compen-

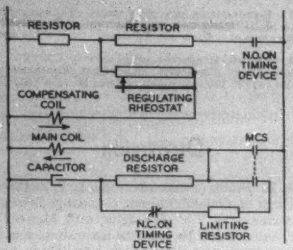

Figure 1

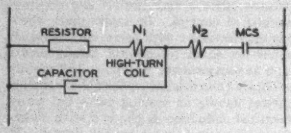

Figure 2

sating coil remains connected to the main bus and for any value of regulating resistance and capacitance, compensation is obtained by proper adjustment of its bucking strength and drop-out spring tension. The only factor which can affect this device adversely is a change in bus voltage which occurs between the time the master-control-switch contact opens the circuit to the main coil and the time the device drops out to the de-energized position. With 100 microfarads capacity, 75,000 ohms discharge resistance, and 16 volts across the compensating circuit, the following time drop-out values for changes in regulating rheostat were obtained:

3,000 ohms—26 seconds
2,250 ohms—22.5 seconds
1,500 ohms—18 seconds
750 ohms—11 seconds
0 ohms—1/5 second

By changing the capacitance, a different range in times may be obtained. Voltage compensation, of course, takes place for any or all the above settings.

The regulating rheostat also gives a means of remote control of time delay when desired. On the above device, when the voltage changed from 150 volts to 280 volts, test results showed a maximum variation of less than one per cent in time drop-out over the complete range.

The authors state that a coil design for a magnet is determined primarily by the pickup value required. However, by using a capacitor, a two-section coil may be designed to give both a high pickup force and an economical holding action. Such a circuit is shown in figure 2.

A high-resistance high-turn coil N_1 is in series with a discharge resistor R, across a capacitor C. N_2 is the second section of the coil consisting of a low number of turns and low resistance, compared to N_1. When MCS is closed the N_1, C circuit draws an initially high surge of current, thus producing the required high force through the open or high-reluctance path of the contactor.

By proper design, a high value of ampere-turns, sustained through an ample time, can be obtained in a very small winding space due to the short duration of the current. The major part of the winding space is then available for the N_1 winding which performs the holding function after the magnet has picked up. The discharge resistor shown is used solely to obtain time delay drop-out.

In an application where fast pick-up and fast drop-out of a contactor is desired, a connection as shown in figure 3 may be used.

N_1 and N_2 are both 6,000-turn coils, the latter having a resistance only $^1/_{20}$ of that

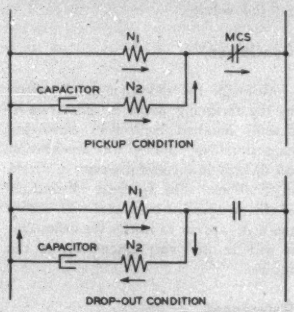

Figure 3

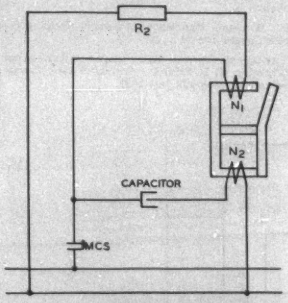

Figure 4

of the former. When contacts MCS are closed, the current rush through N_2 aids normal current through N_1 to give a very fast pickup. On drop-out the coils are in opposition so that the capacitor discharges through a circuit of low inductance and fast drop-out. A contactor connected in this manner picked up in three cycles and dropped out in one to 1.5 cycles, whereas, the same contactor with standard coil picked up in seven to eight cycles and dropped out in four to five cycles.

The following circuit shown in figure 4 is very similar to that shown by the authors in their figure 2. We feel, however, that some operating characteristics may be of interest.

With the connection shown, electrolytic capacitors cannot be used if long timing of great accuracy is required due to their leakage characteristics. With proper magnetic reluctance relationship between the top and bottom magnetic circuit, the time of pickup is only slightly affected by voltage changes. With two identical coils of 26,000 turns and 4,200 ohms resistance, and with C equal to 50 microfarads, the following results were obtained:

Volts	Time Pickup (Seconds)
285	3.0
250	2.9
200	2.7
150	2.7
100	2.8

To prevent change of timing with temperature, a resistance R_3 of zero-temperature-coefficient wire is used in series with the pickup coil to consume about 80 per cent of the power of the circuit.

With the following connection (figure 5) electrolytic capacitors can be used and much longer times can be obtained.

With the same coils and capacitance as in figure 4, the following data were obtained:

Volts	Time Pickup (Seconds)
280	14.0
250	14.1
200	14.0

Figure 6 shows a simple connection where a capacitor can be used in place of an interlock which would normally short out a resistance on starting.

When MCS is closed, the capacitor acts as an initial by-pass for the current, allowing enough flow to pick up the device. The capacitor, on becoming charged, then acts as an open circuit thus putting the limiting resistance in series with the coil.

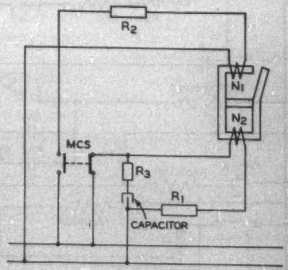

Figure 5

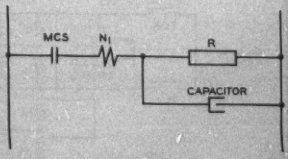

Figure 6

Recent Developments in Telegraph Switching

F. E. d'HUMY
FELLOW AIEE

H. L. BROWNE
NONMEMBER AIEE

IN TIMES when so much thought and attention are given to the streamlined development of modern life, such as aviation, de luxe high-speed trains, airmail, radio, television, sound movies, and other wonders of science, it is quite natural that an industry such as the telegraph should find itself called upon constantly to fill an ever increasing demand for new services or functions created by this world of today. With every new development in modern industry, new needs arise for quick interchange of information—accurate and in written form for permanent record to insure against misunderstanding or forgetfulness. It is these needs which the telegraph, through its system of fast record communications, has been able to anticipate and provide for. Engineering research and developments in telegraphy have fully kept pace with the modern trend, and during the last year or two, there have been brought to conclusion several developments which promise to make the telegraph more necessary than ever to our social and industrial life.

The reperforator switching system of the Western Union is one of these recent products of its engineering laboratories—one that seems destined to change the entire character of the telegraph office, and to advance the art of handling telegraphic communications in a manner fully comparable with other trends of present day life.

It is seldom that new developments embody new principles. Oftener than not, the newest improvements in technology are refinements of what has already gone before. They are what may be considered to be an intelligent fitting together of elements handed to us by our predecessors. Thus the reperforator switching system is but the result of the careful selecting, refining, and fitting together of certain devices and ideas which have come down through the years of telegraph, together with the development of certain new elements which are essential to the success of the system as a whole.

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F. E. d'HUMY is vice-president in charge of engineering and research, Western Union Telegraph Company, New York, N. Y.; H. L. BROWNE is employed by the same company.

Relay Offices

By its nature, telegraph business consists of the transmission, in record form, of multitudinous short messages from a large number of sending points to an equally large number of receiving points. Like a railroad system with its variously routed traffic, the telegraph from its earliest days has been able to function economically only through the medium of central transfer points, or relay offices, each of which has direct connection to numerous originating and destination points, and direct wires to one or more other relay points. At these relay offices, as high as 95 per cent of the telegrams relayed are received over printing telegraph circuits and retransmitted over similar circuits, the only exceptions being those messages handled over Morse-operated circuits or by pneumatic tubes connecting with branch offices.

Obviously this system permits handling the maximum amount of business over a minimum number of wires, but it also requires a considerable amount of manual work at the relay offices. To be more specific, the reception of a telegram in a relay office involves the service of a receiving operator who scans the telegram for errors, times it, marks it off on a tally sheet, and releases it. It is then manually or mechanically carried to a distributing center where it is routed to the circuit over which it is to be retransmitted and is manually or mechanically carried to the terminus of that circuit. The transmission out of the relay office requires the services of a transmitting operator. These offices must be adequately staffed with operators, distributing clerks, and supervisory forces, to insure rapid handling, for telegrams must be at their destinations within a few minutes after they have been filed at the originating point. It was with a view of eliminating as many of these manual operations as practicable and replacing them with a single switching operation that the development of reperforator switching was undertaken.

Early Experiments With Storage Devices

During the many years since Morse first invented the telegraph, there have been developed many devices for the automatic transmission and reception of telegraph signals, all intended to increase speed and improve accuracy. However, there has always remained the impracticability of switching signals directly from an incoming to an outgoing circuit, without creating difficulties on the incoming one while waiting for the outgoing one to clear of other business. These waiting times would either cause intolerable congestion of messages on the incoming circuits, or would be seriously wasteful of valuable circuit time, depending on the type of system employed. In order to maintain continuous high-speed operation, it is essential that means be provided for storing the incoming signals without delaying their reception, for moving them immediately from the incoming to the outgoing circuit terminals, and then for retransmitting them on the outgoing circuit just as soon as the latter is clear.

Thus the elements for a successful switching system for commercial telegraph service must include provision for a distant station to transmit into the switching system at any time and at its own convenience, a means of distributing these telegrams at high speed to the transmitting terminals of the proper outgoing circuits at each of which are accumulated, in one storing device, the telegrams for that circuit, and a means for transmitting these accumulated telegrams as fast as the line will accept them. Finally, all of this should be accomplished so efficiently that when circuits are available, an outgoing telegram will be on its way immediately. In addition to these fundamental elements, there must be numerous devices for check purposes to insure that each telegram is handled correctly.

If space and time permitted, it would be interesting to discuss the many different schemes and inventions which previous workers have evolved for a speedier and more efficient handling of telegraphic communications. But such a study would serve principally to demonstrate, once more, that new developments are often but refinements of old ideas, with certain important changes and additions. It would show, for example, that paper tape perforated with holes corresponding to the telegraph code was

used for automatic sending as long ago as in 1846—only two years after completion of the first telegraph line between Washington and Baltimore. It would show that keyboard perforators for preparing such tape were patented over 80 years ago. Automatic recording by a perforated tape was proposed a few years later, while automatic retransmission direct from recorder tape was proposed about 50 years ago. Other inventions which might call for special mention would include various tape perforators controlled by incoming signals, mechanisms for operating type-setting devices from received perforated tape, and printers operating directly from received tape. There also have been arrangements for both printing letters and perforating tape, simultaneously, from received signals.

Numerous inventors have devised mechanical arrangements for receiving and storing signals, such as pin storage devices using plates, drums, disks, or chains and devices employing balls which were dropped in recesses in "letter blocks" that acted as links in a chain. In general, however, mechanical storing transmitters have not met with much commercial success, largely because they are definitely limited in storage capacity. If large capacity is provided in original design, it proves costly and usually entails parts that are too heavy for high-speed operation.

From the foregoing, it will be evident that the fundamental elements of reperforator switching systems are really not new. In fact, the use of reperforators, or some form of storing transmitter, was contemplated by the Western Union in 1912, when its multiplex system was being designed, and code combinations were actually assigned to permit a sending operator to select a distant printer or reperforator, as the case might be.

Reperforators were used to a limited extent in Western Union service about 1925 in connection with transatlantic picture transmission by the Bartlane system, and during 1930 a six-unit reperforator was developed for retransmitting into quotation service branch circuits. This was later modified for five-unit code and was used in inaugurating timed wire service in 1931. The following year perforating attachments were provided for standard multiplex tape printers and teleprinters, so that a perforated tape as well as a printed tape was produced. Although developed primarily for timed wire service, these attachments found many other applications and proved to be especially valuable in relaying large files, such as from the 1932 Olympic games in Los Angeles and the national political conventions.

The first practical attempt by the Western Union to handle regular telegraph traffic by means of automatic reperforation was made in Newark, N. J., in 1933. In this experiment, each telegram, in perforated tape form, was physically transferred from the receiving position to the outgoing circuit, but the results of the trial almost immediately demonstrated that such an arrangement offered no outstanding advantages over existing methods. The difficulties of reading perforated tape at high speed and handling large quantities of short lengths of paper tape, together with the possibility of delaying telegrams in so doing, seemed to offset any advantages that might be gained in other respects.

From the experience gained at Newark, it was evident that automatic recording and retransmission could not be satisfactorily applied to the handling of relay traffic without means for quickly and easily reading the destination of the telegram when it was received in the form of perforated tape, and also some method whereby the tape could be fed continuously through a transmitter associated with the receiving perforator, thus avoiding the accumulation of tape at the receiving position. It was obvious, also, that facilities must be provided for switching the transmitter to various outgoing lines.

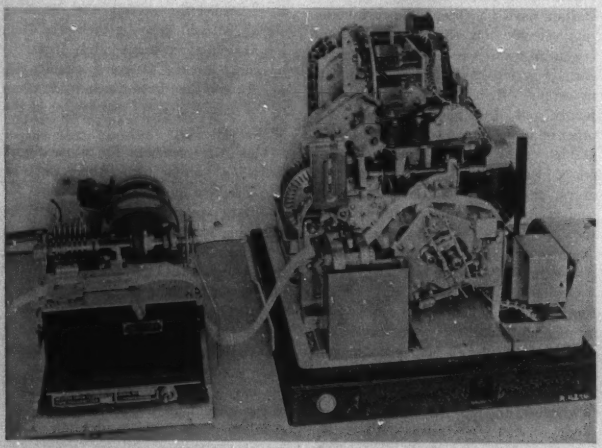

Figure 1. Printer-perforator and transmitter

Development of Reperforator Switching

The next development, therefore, was the embodiment of these various features into a complete reperforator switching system installed at Fort Worth, Tex., in 1934. This installation in its present form employs perforating printers which print letters on one tape and perforate the code on another, and a switchboard at which the transmitter associated with an incoming message is plugged directly to the outgoing connection. This outgoing connection is not the outgoing circuit itself, but an intraoffice circuit which serves to clear the incoming transmitter and transfer the message to a second storage directly associated with the outgoing circuit. This intraoffice circuit operates at 90 words per minute, as compared with 65 on the incoming circuits, and thus can take up the slack caused by any delay in switching. Transmission on the outgoing circuit is automatic and starts immediately, or at least as soon as the line is cleared of other business. Another important feature is the automatic numbering machine on each outgoing circuit, which inserts consecutive serial numbers in all telegrams sent, so that there is a permanent identification for every message.

Later Improvements in Reperforator Switching

The installation at Fort Worth conclusively demonstrated that the general scheme of operation was correct and

that with the system applied to larger offices, particularly those handling a relatively large proportion of relay traffic, substantial improvement in operation could be effected. It also developed the need of further refinement in certain features. The development of these followed, and in October 1937, the present system was placed in operation in Richmond, Va. Of the numerous features

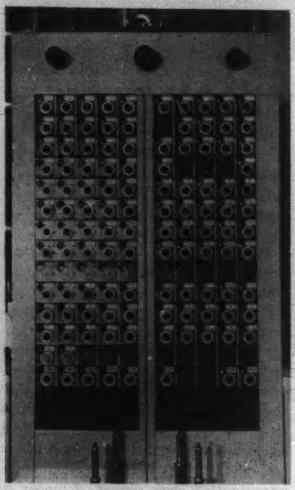

Figure 2. Switchboard

which distinguish this project from the Fort Worth one, most important is the printer perforator, a new printer which simultaneously prints the telegram and punches the code perforations on the same tape, so that the telegram may be read easily by anyone having no knowledge of the telegraph code, and its destination determined as soon as it is received.

Another improvement was the provision for still higher speed on the intraoffice circuits. It was found at Fort Worth that circuits which received continuously for hours, occasionally became congested, due either to gradual accumulation of time employed for switching, or to "waiting time" caused by a needed outgoing circuit being pre-empted by another transmitter. The higher speed necessary to avoid this congestion was obtained through the use of multiwire intraoffice circuits which permitted the transmission of all five impulses of each letter or character simultaneously, instead of consecutively, as in the previous single wire circuits. This arrangement necessitated the development of new high-speed receiving perforators at the outgoing transmitters, but it made possible an intraoffice speed of 125 words per minute. The multiwire circuits were made possible through the development of special jacks and plugs designed to transfer a total of nine circuits simultaneously—five for the code impulses and four for special cord-circuit functions necessary to the switching operations.

Except for a general redesign of the equipment assemblies and arrangements, the only other important novelties incorporated in the Richmond installation were the provision of special switching and storage facilities to permit of differentiation between different classes of business, such for example, as certain rush traffic which requires special handling, deferred rate business which often must be temporarily held in storage, and other traffic which for one reason or another cannot be immediately transmitted to its destination. A more detailed description of the new reperforator switching system follows.

Theory of Operation

In the reperforator switching system which Western Union has installed at Richmond, Va., all printing telegraph circuits terminate in a special switching section. Each of these circuits is, in effect, two circuits, one transmitting and one receiving. All receiving circuits are grouped together in one section of the switching unit, and all transmitting circuits are grouped in another section. Intraoffice circuits between the two sections permit transmission from the receiving section to the transmitting section.

Each receiving circuit terminates in a recording device called a printer-perforator which prints each received character along one edge of a paper tape and simultaneously perforates holes in the tape immediately below the printed character. These holes are printing telegraph code combinations which represent the letter printed above them, and when the tape is passed through a transmitting device they cause that letter to be transmitted. Telegrams may therefore be stored in this paper tape and retransmitted over any other circuit by passing the tape through the proper transmitter (figure 1 shows a printer-perforator and a transmitter).

Each transmitting circuit terminates in a transmitter that is permanently connected to it. Telegrams to be transmitted over these circuits are electrically transferred to them from the receiving positions over intraoffice circuits. These intraoffice circuits are in two parts. One part is formed by a transmitter located immediately adjacent to each printer-perforator in the receiving section, and this transmitter terminates in a cord and plug on the shelf of a switchboard. The other part is formed by a printerless perforator located immediately adjacent to each transmitter in the transmitting section, and it terminates in multipled jacks in all of the switchboards (figure 2 shows a switchboard).

When a telegram is received on a printer-perforator, the perforated tape produced by this device passes through the intraoffice transmitter beside it. The plug of that transmitter is inserted into a selected one of the jacks in the switchboard which completes a circuit to a printerless perforator where the message is again recorded in the form of perforated tape. This perforated tape automatically passes through the line transmitter immediately beside it and the telegram is transmitted to a distant station.

This theoretical description of reperforator switching is, of course, much simpler than the actual operating installation. Many other functions have to be performed in order to make the system practical.

Layout

The switching equipment of all receiving terminals is mounted on double deck-tables in order to concentrate the printer-perforators as closely as possible to the switchboard which serves them, and in order to conserve floor space. Circuits which handle a large number of telegrams are placed in groups of four to each switchboard. In these groups, two printer-perforators, one on the lower shelf and one on the upper, are placed on each side of the switchboard. On more lightly loaded circuits, eight receiving positions are associated with each switchboard. In these cases, two upper and two lower shelf positions are used on each side of the switchboard. A switchboard and its quota of four or eight associated printer-perforators and intraoffice transmitters form a complete receiving terminal unit.

All of these switching units are grouped in two long banks which face each other in such manner as to provide a working aisle where all manual switching functions are performed (figure 3).

Transmitting positions are equipped

with intraoffice automatic perforators, line transmitters, and numbering machines which will be described later. These units are grouped in a separate section of the office on double-deck tables which also face each other to form a working aisle for supervisory and regulating purposes (figure 4).

A third section of the room is formed by manual transmitting and receiving positions similar to those in any other telegraph office (figure 5). Telegrams received over Morse wires or by pneumatic tube or local telephone are transmitted from this section into the switching unit where their handling is identical with the switching operation already described. Telegrams received in the switching unit to be retransmitted over Morse circuits, pneumatic tubes, or local telephone are switched into one of the receiving positions of the manual section where their handling is identical with that in any other telegraph office. There is, however, one difference between these manual positions and those of an ordinary telegraph office. They are not permanently connected to individual circuits, therefore the loads may be concentrated on the fewest possible positions and operators do not have to move from one position to another.

Switching Operations

In the switching section each receiving circuit terminates in a printer-perforator which serves that circuit alone. The printed and perforated tape which comes out of that instrument tends to form a loop between the printer-perforator and the intraoffice transmitter. This loop drops into a glass tank immediately under the printer-perforator and accumulates there until the intraoffice transmitter functions to transfer it across the room to the transmitting positions. The intraoffice transmitter will not operate, however, until a connection has been established through the switchboard. Since this connection is not started until a telegram has been completely received, some accumulation of tape is normal. This accumulation may at times exceed one telegram due to the fact that one switching clerk handles several receiving circuits, but the quantity of unswitched tape on hand is always visible to the clerks and supervisors. Any accumulation of tape which will require more than a minute or two for intraoffice transmission is given continuous attention by the clerk until it has been eliminated.

Before a tape can be switched, it is necessary for the clerk to ascertain its destination and select the switchboard jack connected to the proper transmitting circuit. The printed characters on the tape facilitate this operation. The destination usually appears in the tape about eight inches from the beginning and is readily visible to the clerk.

After noting the destination, the clerk picks up the plug associated with that transmitter and inserts it in the jack of the switchboard which serves the desired transmitting circuit. This operation completes the clerk's work on that particular telegram and she is free to proceed to another circuit.

It is essential that this manually performed portion of the switching operation be completed on the first attempt by the clerk with no waiting. It must be possible for her to insert plugs into jacks whenever that operation is most convenient, and leave all subsequent operations to the functioning of purely automatic equipment. There are frequent occasions when two or more transmitters will have need for the same intraoffice circuit simultaneously, therefore there must be a plurality of jacks in each switchboard which serve the same intraoffice circuit, and each intraoffice circuit must be multipled to all switchboards.

Circuit Allotter

In order that plugs may be inserted simultaneously in these multipled jacks without interrupting one another, a device known as a circuit allotter is used. When a plug is inserted in a jack of the switchboard only a potential connection is established. A plurality of simultaneous potential connections to the same intraoffice circuit are converted one at a time into actual connections through the action of the circuit allotter. This allotter breaks the existing connection at the end of each message and establishes an actual connection from one of the potential connections, repeating this operation until there are no more potential connections.

The circuit allotter is caused to function at the end of each telegram by a special signal which is transmitted by the station which transmits the telegram into the Richmond office. This signal is two periods and one space. It is essential that intraoffice connections be broken at the end of each telegram in order that each telegram may be individually routed over that circuit which will give it the most direct path to its destination. It is the exception rather than the rule that two consecutive telegrams received over any interoffice circuit will be destined to the same outgoing circuit. Therefore all intraoffice transmission is "single shot" or one switchboard operation for each telegram. The intraoffice transmitter, of course, is stopped automatically after each telegram. If a plug is left in a jack after transmission is completed on the telegram for which the connection was established, it will not interfere with subsequent use of the intraoffice circuit by other positions and the circuit allotter will not subsequently re-establish the connection unless the plug is removed from the jack and then reinserted. These operations on the part of the circuit allotter make it practicable for the switching clerk to insert plugs in jacks immediately upon arriving at a switchboard, and then remove that plug from the jack at any convenient time after transmission is completed.

Numbering Messages

Experience has shown that certain safeguards are needed in handling telegrams. One of these safeguards is the use of identifying numbers. These numbers which are in consecutive order starting with number one each day, are affixed and transmitted by transmitting stations and are checked off on number sheets by the receiving stations. Each circuit has its individual series of numbers, therefore a telegram received over circuit *A* under one number, will in all probability be retransmitted over circuit *B* under a different number. This enables the two terminals of each circuit to maintain a constant check on transmission.

In the reperforator switching system it was found to be impracticable to manually insert numbers on telegrams when they were retransmitted. A method was therefore devised to insert these numbers automatically. In order to serve their purpose, numbers must not only be transmitted, but a record must be made at the transmitting office which will indicate which number was assigned to each telegram. This is accomplished by inserting an automatic numbering machine in the intraoffice circuit between the switchboard jack and the automatic perforator on the transmitting circuit. It thus becomes a part of the apparatus associated with the transmitting terminal. When an intraoffice connection is established through the insertion of a plug in a jack and the ensuing operation of the circuit allotter, the automatic numbering machine instantly pre-empts the circuit, transmits its next consecutive number into the automatic perforator and then establishes the connection between the

Figure 3. Switching aisle in receiving section, Richmond, Va.

Figure 4. Supervisory aisle in transmitting section

automatic perforator and the transmitter which selected it. The transmitter then starts automatically and transmits its message. The perforated tape produced by the automatic perforator for transmission on the outgoing circuit will then have the next consecutive number for that circuit immediately preceding the telegram. The tape serves as a record for the switching office to show the relationship of all numbers and their associated telegrams.

Supervisory Measures

In addition to the apparatus employed in the actual handling of telegrams, there are many supervisory devices to facilitate operation and insure safety. In order that switching clerks may know when a telegram has been received on a printer-perforator and is waiting to be transferred through the switchboard to a transmitting circuit, a signal lamp mounted on top of each switchboard lights when a message starts arriving on a printer-perforator served by that switchboard. This indicates to the clerk that a telegram is being received in that group of circuits. Another lamp mounted in a signal indicator panel individual to each printer-perforator also lights to indicate the particular circuit over which the telegram is coming.

In order to provide visual supervision of the functioning of the intraoffice circuits, two small signal lamps are mounted adjacent to the seat of each transmitter plug flush with the switchboard shelf. When a plug is inserted into a jack of the switchboard, one of its lamps will light and remains lighted until the intraoffice connection has been completed and transmission started. When transmission of each telegram is completed, the second lamp will light, indicating that the connection has completed its function and the plug may be removed from the jack.

Since there is a distance of several inches between the punch block of the printer-perforator and the transmitting pins of the transmitter, it is necessary to step out a few inches of blank tape at the end of the last telegram in a group, in order that the last character received may pass through the transmitter. On receiving circuits, push buttons are installed which, when manually depressed, will cause the printer-perforator to step out a predetermined length of blank tape. On transmitting circuits, when the tape between transmitter and automatic perforator becomes taut, the automatic perforator will automatically step out enough tape to allow the last character to pass through the transmitter. When the tape again becomes taut after this operation, no more tape will be stepped out until another telegram has been received.

It may happen that the tape produced by one of the automatic perforators on the transmitting circuits may become broken or jammed in the punch block, or the center holes of the tape stripped so the transmitter will not pull it through. It is very important that such a condition be detected quickly and that the intraoffice connection be maintained until the trouble has been corrected so that a rerun of the tape may be secured. If the connection to the intraoffice transmitter is broken it will be difficult to determine from which transmitter the telegram came. In order to obviate this, alarm circuits are set up to attract attention and to hold the existing intraoffice connection. On the automatic perforator the tape passes between two rollers. The shaft of one roller carries a cam which actuates two sets of contacts in such manner that failure of the tape to move properly while signals are being received by the perforator sets up an alarm signal. When this happens, the action of associated relays will cause the intraoffice transmitter to stop and trouble signals will appear at the automatic perforator position and also at the transmitter position. The circuits are so designed that the trouble at the automatic perforator may be cleared and then by depressing a push button leave the automatic perforator in readiness to function as soon as the tape has been reset in the transmitter. After the tape has been reset at the transmitter, depressing the push button at that position causes the transmitter to start. Transmission cannot be resumed, however, until the push buttons have been operated at both the automatic perforator position and at the transmitting position.

In addition to the problems which concern the actual movement of telegrams, there are problems which relate to good service. Certain classes of telegrams require more expeditious handling than usual. They must be given precedence over other telegrams already in storage or in the process of transmission. In order to accomplish this end, a special position known as the *X* center has been installed. Urgent telegrams are switched direct to this position through special jacks and intraoffice circuits. They are received at the *X* center on printer-perforators in order that their destinations can be quickly read. The transmitters are connected to cords and plugs like the receiving positions of interoffice circuits. A special switchboard serves this center and the jacks are so connected that when a plug is inserted in them, the transmitter at the regular transmitting position is disconnected and stops transmitting, while the transmitter of the *X* center picks up and pre-empts that circuit until transmission of the urgent telegram is completed, at which time the circuit is

restored to its regular transmitter which resumes transmission. Urgent telegrams may be and frequently are transmitted in between the first portion and the last portion of ordinary telegrams just the same as in manual transmission.

Traffic Routing

One of the most important operating features is the routing of telegrams to the circuits which have been designated by the circuit layout and routing engineer as the path over which they shall transit. While Richmond has direct connections with many cities, telegrams are received destined to all parts of the world. Direct connection between all cities and towns is obviously impracticable and it is necessary that telegrams be directed toward various offices having connections with the different cities not reached by Richmond. To systematize the handling and to insure that relay messages receive the minimum number of handlings, routing charts are provided and maintained at each relay office. These charts indicate the proper routing of telegrams for points not worked direct.

Complete route charts, covering outside cities, and the distribution between the various branch offices in Richmond, are located between alternate switchboards. This insures that a clerk will be not over five feet from routing charts at any switchboard.

In case a direct circuit fails, it is necessary to route the traffic over some alternate path and continue this routing until the direct circuit is restored. A small neon lamp associated with each jack indicates the condition of that circuit. When a circuit fails, transmission on it stops, and lights at all switchboards indicate that connections are not to be made to that circuit. It is impossible for a transmitter to start if a connection is made to that circuit and the signal lamp commences flashing and continues to do so as long as the plug remains in the jack. All clerks are notified immediately of irregular routings. This information is placed on a blackboard located so that it is visible from any part of the switching aisle. Information regarding irregular routings is immediately placed on this board, and switching clerks immediately start transmission over the irregular paths.

Spill-Over Positions

Certain practical problems connected with operation make it desirable to provide a means of giving special supervision to some of the telegrams transiting through a relay office. In order to meet this requirement at Richmond, four special positions, termed "spill-over positions," are provided. They are similar to the regular receiving positions, having printer-perforators, intraoffice transmitters, and switchboards. When a telegram is to be handled through one of these spill-over positions, a connection is formed through the switchboard in the receiving section to an automatic perforator in the transmitting section. The tape from this automatic perforator passes through another transmitter which transmits into a printer-perforator at the spill-over position. The reason for passing the telegrams through the automatic perforator rather than directly into the spill-over printer-perforator is due to the fact that the intraoffice transmitters on receiving positions transmit at a speed of 125 words per minute and automatic perforators can accommodate this speed, but printer-perforators are designed to operate at line wire speeds of about 60 to 70 words per minute. Therefore it is necessary to transmit from receiving section to automatic perforator at high speed and then retransmit at lower speed into the printer-perforator of the spill-over position. It is necessary to have these telegrams at the spill-over position in printed and perforated form in order to facilitate supervision and expedite retransmission away from the spill-over position. One of the uses of the spill-over position is in connection with telegrams destined to the smaller communities where the telegraph office is closed at night and for a period of the day on Sundays. During the hours when these small offices are closed other means of getting important telegrams to these points are adopted. Sometimes they are sent to the railroad office in the city of destination, and sometimes they are transmitted to a nearby larger city from which point they are telephoned.

All telegrams destined to closed offices receive close censoring at the last relay office in order to determine whether or not they should be held for the office to open or if other action is necessary. This censoring cannot be delegated to switching clerks, therefore when the signal light on the switchboard indicates that a circuit is closed, the switching clerk switches the telegram to a designated spill-over. Full-rate telegrams and deferred-rate telegrams are transmitted into separate spill-overs. The supervisor censors these telegrams and takes any necessary action. If no action is necessary, full-rate telegrams are immediately switched from the spill-over into the regular storage position and held for the office to open. The deferreds are switched into the regular storage positions some time in the early morning, prior to the opening of the office. As the full rates were switched earlier and are already in the tape at the transmitting position, the outside office first receives these full rates and then the deferreds.

The spill-over positions can be used as sidetracks for telegrams to be held pending restoration of failed circuits in those cases where an alternate routing cannot be obtained.

Double Storage

In the foregoing description of reperforator-switching at Richmond, it has been shown that telegrams are stored twice in the switching office—once at the printer-perforator on the receiving circuits and again at the automatic perforators on the transmitting sides of circuits. It has also been shown that the intraoffice transmission between these two perforators is at a speed of 125 words per minute. The reasons for this "double storage" and "high-speed intraoffice transmission" will now be discussed in more detail.

It would be possible to connect the transmitting terminals directly to jacks in the switchboard and switch the signals received on printer-perforators directly to the outgoing line. That would dispense with the need for intraoffice circuits and secondary storage in automatic perforators on the transmitting terminals. Much less equipment would be required and theoretically the handling would be faster because it would be more direct. Such an arrangement is impracticable. however, where a large number of telegrams are relayed between a multiplicity of circuits. Reception on certain circuits will be continuous for hours. Since the speeds of all circuits are approximately equal, it is apparent that transmission away from the printer-perforators could never be faster than reception. Actually it could never be as fast due to the time required to perform the switching function and due further to the fact that at times the transmitting circuit sought by a printer-perforator would be pre-empted by another printer-perforator. Under such circumstances the number of stored messages would increase steadily and continuously. In order to avoid these difficulties it is necessary to transmit away from the printer-perforators at a rate of speed that is much higher than reception. This intraoffice speed is

125 words per minute, as described later. As the outbound circuits will not accommodate such speed, it is necessary to provide an intermediate handling and step this speed down to approximately 65 words per minute. This is accomplished by using high-speed automatic perforators as individual storage bins, each of which accumulates all of the messages that are to be transmitted over one circuit. This creates a condition where messages are accumulated on transmitting terminals over intraoffice circuits at 125 words per minute and transmission to line is at a speed approximately one-half as fast. This condition is not undesirable, however, for transmission to line is continuous as long as there are telegrams on hand to transmit while reception into the secondary storage over the intraoffice circuit is intermittent. If the total volume of traffic to be transmitted over an interoffice circuit is greater than a speed of 65 words per minute can accommodate satisfactorily, additional facilities must be provided. In this respect the problem is identical with similar conditions under manual operation and is not peculiar to the switching method.

The method used in achieving an intraoffice speed of 125 words per minute has been referred to previously, but it is interesting and will be described in some detail. In printer telegraphy each letter, figure, character, or function is selected by the transmission of five electrical impulses. Individual selection is through the various possible combinations of positive and negative impulses in groups of five impulses per character. The total possible number of selections is approximately doubled by printing one character when the printer is in the lower case or letter shift position and another character when the printer is in the upper case or figure shift position, for each combination of impulses.

On all interoffice telegraph circuits the five impulses of each character are transmitted consecutively, each impulse having the same length or duration of time. By means of synchronous operation of the transmitting and receiving devices, each impulse in a group of five controls an individual selecting magnet, therefore each group of five impulses sets up the selection of a character in the receiving printer.

It is possible greatly to increase the speed of transmission by using five wires between the transmitter and the printer and transmitting all five impulses of a character simultaneously. The cost of providing five wires on interoffice circuits is prohibitive and is not used on such circuits. At Richmond, however, the five-wire system is used in order to provide the intraoffice speed of 125 words per minute. By this means an accumulation of messages at the printer-perforator position can be disposed of at a speed approximately twice as fast as they are being received. This high speed also reduces the time that an intraoffice connection is being used, thus reducing holding time from the various switchboards.

It was necessary, in order to use the five-wire system, to develop special plugs and jacks. These carry nine conductors and the plugs are formed by metallic rings separated by nonconducting rings. The jacks have spring contacts that are so spaced that they fit the metallic rings of the plugs. The four extra connections are used in control and signal circuits (figure 6).

While the plugs are larger than the present standard telegraph and telephone plugs, no difficulty has been experienced by the clerks in manipulating them. The jacks and signal lights occupy about one square inch each on the surface of the switchboard but the switchboard has not proved too large for fast switching. With a much larger installation, it may be necessary to reduce the size of the jacks and plugs, in which case a cam switch or a control plug with relay banks may be substituted.

Conclusions

In concluding this discussion of reperforator switching, it seems in order to summarize briefly a few of the results which have been realized in the Richmond installation since its operation started on October 16, 1937. First, relay business moves through the office in about one-quarter of the time required with manual operation. Second, the capacity of intercity circuits has been increased practically 25 per cent due to the fact that transmitters function continuously as long as there are telegrams to be transmitted. Under manual operation, an operator cannot always keep the transmitter busy, even when there are telegrams awaiting transmission.

Another result is a gain in accuracy, due to the elimination of manual reperforation for the retransmission of each telegram. Finally, operator production, under both average and peak load conditions, has been increased substantially. In spite of this increase, the physical and mental effort required of the operating personnel is much less than in other methods of operation. There are also advantages from the central-office standpoint, since the manual and mechanical distribution of telegrams about an office is done away with and the office equipment occupies considerably less floor space than that used previously.

The Richmond installation has successfully withstood every test of practical operation, and has demonstrated its superiority under all conditions. In

Figure 5. Operating positions in manual section

Figure 6. Jack and plug used in nine-wire transmission

Surge-Voltage Breakdown Characteristics for Electrical Gaps in Oil

ROYAL W. SORENSEN
FELLOW AIEE

Synopsis: This paper, emanating from a request for information regarding surge voltages required to break down gaps in oil, gives surge breakdown voltage values with different gap spacings for 1/4-inch, 1/2-inch, and 1-inch round rod electrodes with hemispherical ends immersed in transformer oil. As expected, these values are a function of "time to breakdown" but for each condition curves show constant breakdown values for breakdown times of the order of about 16 microseconds and longer with the 1 1/2 x 40 negative wave, used on all the tests reported. Particular attention is called to the relatively small amount of oil required for tests of this type, made possible by the special type of test barrel used.

INSULATION co-ordination and oil-circuit-breaker designs make desirable a knowledge of surge voltages required to break down insulating oil. The lack of data pertaining to this subject was called to our attention by E. K. Sadler and J. L. Thompson, engineers with the Kelman Electric and Manufacturing Company. The test results published in this paper were made possible by the co-operation of J. N. Kelman, who provided some of the equipment required for making the tests, and by a great deal of arduous and careful work done by graduate students, particularly G. D. McCann and A. E. Harrison, in the high-voltage laboratory at the California Institute of Technology.

Voltage for making the tests was obtained by means of a 1,500,000-volt Marx circuit surge generator comprising 30 50-kv 0.5-microfarad General Electric capacitors and a suitable d-c charging circuit. The test gaps in oil were formed by using specially constructed electrodes assembled in a test barrel devised by the author and shown in figures 1 and 2. All tests were made with a standard 1 1/2 x 40 negative wave. The voltage for each discharge was measured by means of a cathode-ray oscillograph of the cold-cathode continuous-beam type designed and built by Doctor Howard Griest,[1] and a resistance potentiometer constructed according to the required standards for such work. Figure 3 shows a typical oscillogram. The voltages thus measured were at intervals checked as to peak values by comparison with standard sphere gaps.

All gap test electrodes used were round rods terminating as hemispheres having the same diameter as the rods. This type electrode was chosen in preference to spheres mounted on rods or shanks in order to avoid under surge conditions, uncertainties regarding the influence of shank diameter upon the field uniformity around the gap, and, hence, upon the results obtained by our tests.

Electrodes ranging from one-fourth inch to six inches in diameter were prepared. This report contains data for electrodes having diameters of one-fourth, one-half, one inch, and two inches, respectively. The data for the two-inch electrodes are less complete than for the other rods, because the voltage available, 1,500 kv, would not permit tests with the two-inch electrodes at the larger spacings. An increase in surge-generator voltage is being made and further tests will be reported in a later paper.

One reason for the absence of data of the type presented in this paper has been the difficulty encountered in providing a convenient lead-in bushing for making tests of this type. This difficulty we overcame by making a test barrel in which the electrodes were mounted, and its lead-in bushing of insulating material having about the same dielectric constant as insulating oil. Fortunately, we had available for making this device two cylinders made of paper and varnish, known by the trade names Micarta and Herkolite, respectively. The larger cylinder, 40 inches in diameter and 72 inches long, forms the test chamber, and the smaller one, 23 1/4 inches in diameter and 48 inches long, serves as a lead-in bushing. These cylinders were open at both ends when obtained. An oil-tight bottom for the test barrel was obtained by placing the insulating cylinder upon a steel plate on the surface of which a circular gasket seat had been machined. A cork gasket which could be clamped tightly between the end of the cylinder and the gasket seat was used. A steel clamping band, as shown in figure 2, drawn tightly around the Micarta cylinder by a bolt and drawn down hard upon the cork gasket by bolts through studs welded to the band and engaging threaded holes in the steel bottom, provided means for keeping this cork-gasket joint tight. Any oil leakage which might occur, due to accident or other cause, was amply provided for by placing the test barrel in a shallow oil-tight steel receptacle, large enough to hold all the oil used. With this arrangement, requiring only eight barrels of oil, the test electrodes are freer from field distortion due to adjacent materials than would be possible with the use of containers of metal or other conducting or even semiconducting material, unless such containers were made very large. That is, the use of oil in a barrel of insulating material having about the same dielectric constant as oil, makes possible with a small amount of oil, electric gaps immersed in what, in effect, is a column of oil insulation surrounded by the atmosphere of the test room.

Calculations before construction, and tests after construction, show, for all practical purposes, that this device provides a means of having test gaps in oil completely free from field distortion due to surrounding objects.

The Herkolite cylinder serving as the lead-in bushing is closed at the lower end with a fiber and metal bottom designed to hold oil between it and a steel tubing concentric with the insulating cylinder and through which the upper and adjustable electrode extends into the test barrel. This metal part of the bottom is constructed in such a way as to provide for a well-distributed electric field around the

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ROYAL W. SORENSEN is professor of electrical engineering at California Institute of Technology, Pasadena.

1. For all numbered references, see list at end of paper.

periods of subnormal loads, such as Sundays and late night hours, it permits the highest degree of concentration of work. In times of abnormal loads, such as Christmas, New Year's, Easter, or special events of national interest, it expands naturally to accommodate itself to the increased burden. Under all conditions, it handles the telegrams with greater speed and accuracy than ever before, and thus has brought about significant progress in the telegraphic art.

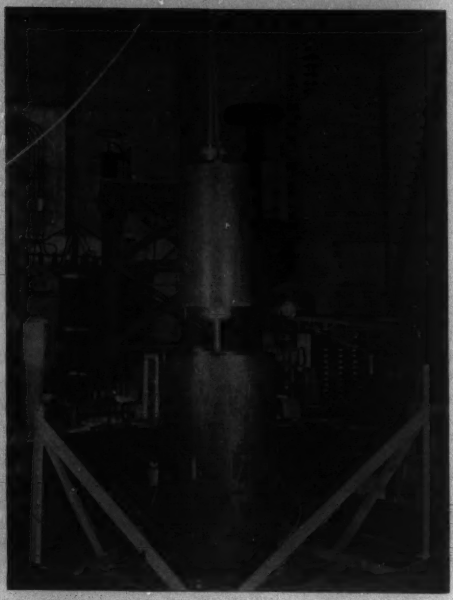
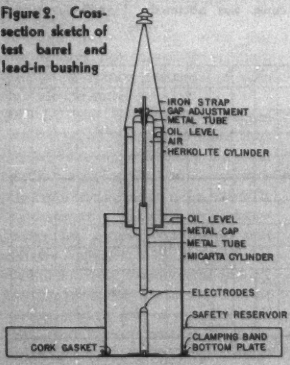


Figure 1. Test barrel and lead-in bushing showing bushing raised for examination and polishing electrodes

lower end of the bushing. The lower electrode, supported by and attached to the bottom of the barrel, was not made adjustable, but constructed so as easily to be changed or removed for cleaning and polishing. During tests the part of the lead-in bushing between outer and inner cylinders is kept filled with oil and flashover from lead-in conductor to the barrel is avoided by having its lower end project into the test barrel a few inches below the surface of the oil in the barrel. This arrangement was proved entirely satisfactory as a means of limiting all arc-overs to the test gap.

Figure 2. Cross-section sketch of test barrel and lead-in bushing



The tests reported in this paper show only the surge voltages required to break down gaps in oil formed between spherically ended cylindrical electrodes of different diameter. All oil used was carefully selected, filtered, and tested according to standard oil testing practice before starting the tests and as often during any test as was necessary to keep the dielectric strength at top value, this top value being determined by a standard oil gap test set capable of applying 30 kv to the one-tenth inch test gap formed between one-inch-diameter flat electrodes. The oil was considered in proper condition when it would not break down for a two-minute application of this voltage. To keep the oil up to this standard during a test program was not easy, filtering often being found necessary after only a few oil punctures had been made; and frequently after the puncture value of the oil had been decreased, it was necessary to put the oil through the filter several times to restore its dielectric strength to 30 kv. Whenever the dielectric strength of the oil dropped to a value of 22 kv or less, the surge voltage required to break down any given gap was reduced an amount which indicates that perhaps as further tests of this type are made, the dielectric strength of the oil during a test run should be determined after practically every oil breakdown. Also, if we wish to know the reason for some of the variable results obtained, it may be necessary to determine oil puncture strength with a precision which will show small variations in dielectric strength in the range above 30 kv, as determined with the standard test cup.

Early in our test program we found that, for consistent breakdown values, only a few discharges could be made between electrode polishings. This was more noticeable for the smaller electrodes than for the larger ones. On rare occasions only one or two discharges which, perchance, occurred from the same spot on one of the electrodes, would make necessary a repolishing of electrodes before consistent breakdown values could be obtained. In all tests it was necessary to observe a time interval of not less than 5 minutes between successive discharges, and for the longer gaps time intervals of 15 to 20 minutes were required for the oil to return to what might be called a normal state.

These influence factors, plus the all-prevailing time-lag influence upon surge-breakdown values of voltage for gaps in oil, added to those well-known difficulties encountered in obtaining similar data at power frequencies, soon made evident the fact that breakdown values for gaps in oil would have to be considered as statistical values obtained from a large number of tests, some of which would show values of breakdown voltage varying a considerable amount from any curve drawn to show the probable reasonable breakdown values. In fact, surge-voltage-breakdown values in oil seem to be even more sensitive to the influences which make testing such gaps at power frequency a major operation, than is the case for the power-frequency tests; and it may almost be said that on some days sport breakdown values occurred, for which there just seems to be no way of accounting.

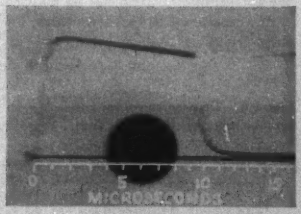


Figure 3. Typical oscillogram, showing oil puncture occurring at 860 kv crest and 9½ microseconds time lag for eight-inch gap, one-half-inch-diameter electrodes

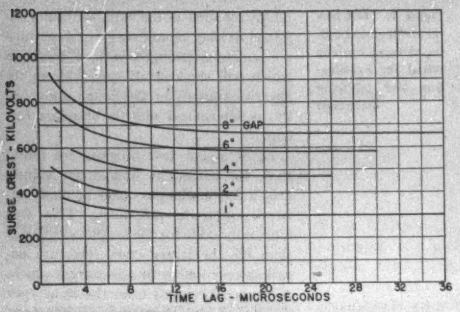


Figure 4. Time-lag curves for one-fourth-inch electrodes with hemispherical ends, 1½x40-microsecond wave

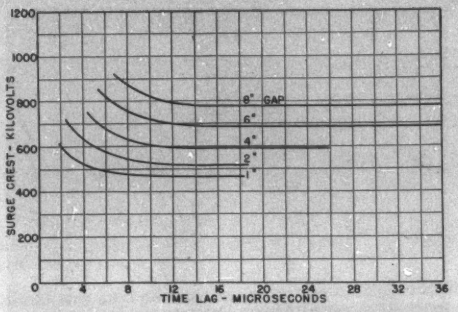


Figure 5. Time-lag curves for one-half-inch electrodes with hemispherical ends, 1½x40-microsecond wave

In making the volt-time tests, the operating procedure was as follows: The surge generator was adjusted to give a 1½x40-microsecond negative wave having a crest value well below the minimum flashover voltage required to strike across the gap under test, and for this setting a surge was applied to the gap. The voltage was then increased by small steps until a voltage was reached which would puncture the oil in the gap. When breakdown occurred, the surge voltage which first caused breakdown was applied a number of times. If breakdown occurred for every surge application, the voltage setting on the generator was reduced until breakdown stopped, after which the voltage was again raised until it reached the minimum value which would give breakdown for a majority of the applications.

As a check on this breakdown value, the surge-generator voltage would be alternately raised and lowered above and below the probable breakdown values. Often a one-step change on the surge generator (about three per cent) in the crest voltage value either way would change breakdown performance so that with a three per cent lowering of the crest voltage there would be no breakdowns at all; whereas with a three per cent increase in crest voltage practically every surge application would cause a breakdown.

Having in this way established the probable minimum breakdown voltage for a given gap setting and electrode size, the balance of the volt-time curve was obtained by applying the 1½x40-microsecond wave at increasing voltages and taking cathode-ray oscillograms of the voltage across the oil gap under test. For each surge-voltage application an oscillogram was made to show the value of the wave from the time of tripping the circuit to breakdown. Figure 3 is a typical oscillogram. In most cases breakdown occurred on the tail of the wave. The crest values of the waves thus recorded were plotted as ordinates on the curve sheets shown in figures 4, 5, 6, and 7, with the time to breakdown shown as corresponding abscissas. The curves thus obtained show minimum breakdown voltages and breakdown voltage versus time to breakdown for higher voltage values. Figure 7 shows the same curve for two-inch spacing, as shown on figure 6, but shows also the exact location of the points used in plotting the curve.

The probable breakdown curves shown in the paper are considered correct as to values given for prevailing conditions within a value of plus or minus three per cent. Occasionally, however, voltages more than ten per cent above the probable breakdown values shown in the curves would be required to cause breakdown. We think such discrepancies were due to undetermined variable conditions of oil and electrode surfaces, but up to the present time our analysis does not permit a statement as to what these conditions were.

When one of these extremely high first-breakdown voltage conditions was encountered, the test procedure outlined

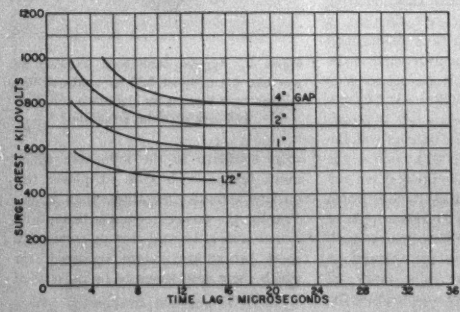


Figure 6. Time-lag curves for one-inch electrodes with hemispherical ends, 1½x40-microsecond wave

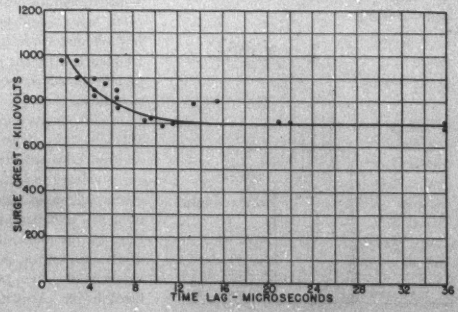


Figure 7. Time-lag curves for one-inch electrodes with hemispherical ends, showing spread of actual plotted values from which curve was obtained, 1½x40-microsecond wave

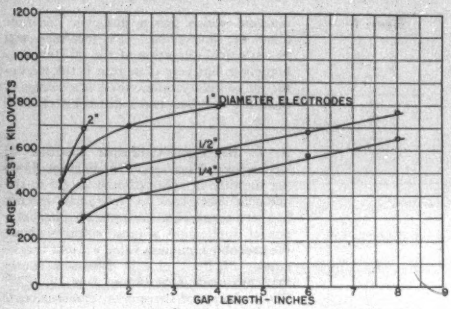


Figure 8. Curve showing relation of gap length to minimum surge crest voltage required for breakdown between cylindrical electrodes with hemispherical ends immersed in oil, 1½x40-microsecond wave

was reversed and, subsequent to the first breakdown, surges of lower crest voltage than the one causing this first breakdown, but higher than the recognized minimum breakdown, were applied. The voltages for the successive tests were gradually reduced until the probable minimum breakdown voltage for any given gap was reached. The minimum values of voltages found in this manner were in agreement with those found for the same gaps by the more commonly used increasing-voltage procedure. For the one-fourth-inch rods no excess-voltage first breakdowns were in evidence. For the one-half-inch rods this effect was indicated only, and then was limited to the longer gaps. The one-inch rods showed a very pronounced tendency to be subject to this phenomena at small spacings and for the longer gaps high breakdown points definitely occurred. The two-inch rods showed occasional high breakdown voltages for short gaps. If continued tests show any appreciable increase in the percentage of high-breakdown-voltage values, it may be necessary for the larger electrodes to indicate arc-over voltage by a broad curve showing the spread, rather than by a single-line probable-breakdown curve.

To show more explicitly what this phenomenon of high breakdown signifies, the following specific instances of such occurrence are noted.

July 11, 1938, five successive surges, all with crest voltage values more than 10 per cent above the probable minimum breakdown value applied to the one-inch gap between one-inch electrodes, failed to puncture the oil. The sixth, or puncturing surge, had a crest value 24 per cent above what appears to be the probable minimum puncture value for the gap.

July 13, 1938, with the same electrodes and same setting, five surges with crest voltages more than 10 per cent above the probable minimum breakdown voltage failed to puncture the oil. Puncture finally occurred at a crest voltage 17 per cent higher than the probable minimum.

July 14, 1938, seven surges which failed to puncture the oil had crest values more than 10 per cent above the probable minimum value applied to one-inch electrodes spaced for a two-inch gap. The breakdown finally occurred at a crest voltage 21 per cent higher than the probable minimum value for this arrangement.

Figure 8 shows data rearranged to enable one to obtain readily the relation between gap lengths and minimum puncture voltages for the gaps included in this report.

It is well to note that the limited amount of data available for design calculations as gleaned from the 1,500 surge tests made to obtain the data presented in this report point strongly to the need of continuing this work in a broader test program extended to a number of our high-voltage laboratories. A search for data pertaining to similar tests for a-c 60-cycle voltage which might be used in making comparison between 60-cycle and surge dielectric strengths of oil gaps[2] disclosed the fact that published 60-cycle data in agreement as to values for gaps formed between different types of electrodes in oil are by no means adequate for our present requirements. Although the ratio of surge crest 1½x40-microsecond wave voltages to 60-cycle crest voltages required to puncture oil when such voltages are applied to immersed sphere gaps varies with the size of spheres and gap spacing, the present available data indicate that no great trouble will be encountered in designing apparatus if this ratio of crest surge voltage to power-frequency root-mean-square voltage is taken as three to one until sufficient data for better conclusions are available. Tests made by F. W. Peek[3] when he introduced the idea of time lag show this ratio of three to one for surges of unknown wave form as compared to 60-cycle breakdown voltages in oil.

To obtain these further data, we invite co-operation from others interested in high-voltage phenomena and recommend the use of test barrels and lead-in bushings made of insulation material having about the same dielectric constant as the insulating liquids to be tested and built according to the general plan of the apparatus described in this paper.

References

1. A Low-Voltage High-Speed Cathode-Ray Oscillograph, R. Howard Griest. Thesis for doctor of philosophy degree, California Institute of Technology, 1937.

2. Oil Breakdown at Large Spacings, Douglas F. Miner. AIEE Transactions, 1927, page 248.

3. Dielectric Phenomena in High-Voltage Engineering (a book), Peek. McGraw-Hill Book Company, 1929, page 227.

Discussion

D. C. Prince (General Electric Company, Philadelphia, Pa.): This paper adds valuable information to our store of knowledge on the behavior of insulating oils. One point of particular value to circuit-breaker designers is brought out very clearly. Under all the conditions investigated the oil presents an impulse ratio of from 2 to 3. Ordinary air clearances, rod gaps, bushings, and the like, associated with circuit breakers, have impulse ratios of the order of 1.2. It follows that failure of the oil under impulse is not limiting, a fact of obvious value to designers.

V. M. Montsinger (General Electric Company, Pittsfield, Mass.): Professor Sorensen has given us some very interesting impulse data on the breakdown of oil. Apparently, by exercising great care, he has been able to eliminate the wide variations in oil-breakdown values that usually occur in ordinary methods of testing.

There are, however, two or three points I wish to comment on.

The author apparently used hemispherical-shaped electrodes to simulate conditions in circuit breakers. The variation of the breakdown voltage with spacing does not seem to follow any law that I have ever observed. For example, his figure 8 shows that for the one-fourth-inch and one-half-inch-diameter electrodes the breakdown voltage varies roughly as the spacing raised to the 0.37 power. For one-inch-diameter electrodes the exponential value of the spacing is even less than 0.37 and bends over, indicating that considerably greater spacings than four inches would give very little increase in breakdown values.

Generally when spheres are used with spacings several times their diameter they act like sharp-cornered electrodes, so far as breakdown versus spacing is concerned. This is especially true when air is the insulating medium.

We have a large amount of data on breakdown of oil for square-edged and round

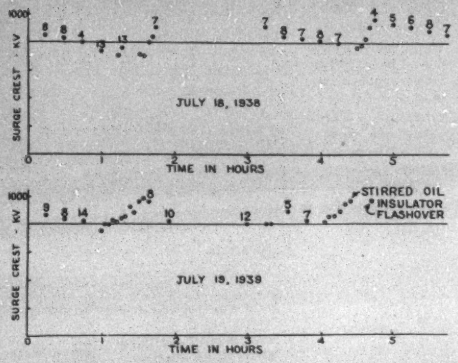


Figure 1

rods (both parallel and at right angles) and in all cases the breakdown is roughly proportional to the spacing raised to the two-third power. It appears from Professor Sorensen's data that for limited spacings—up to six or eight inches—and with small diameter electrodes, the breakdown voltage increases quite slowly with spacing. It would be interesting to know if circuit-breaker engineers find that this is true for the kind of electrodes used in circuit breakers, or do they find that the breakdown strength varies roughly as the spacing raised to the two-third power.

Eric A. Walker (Tufts College, Medford, Mass.): The paper by Professor Sorensen on the "Surge-Voltage Breakdown Characteristics for Electrical Gaps in Oil" is of considerable interest to me because it is very similar in nature to a study which has been started at Tufts College.

In making surge breakdown tests I have felt that one of the most important factors in determining the breakdown strength of the oil is the amount of moisture the oil contains; a factor which is not mentioned by Professor Sorensen, except to say that the oil was periodically filtered.

Oil in contact with air undoubtedly contains water in two forms: water in solution and water suspended as small droplets which gradually settle out and collect as free moisture at the bottom of the tank. The balance between the two types is controlled by the temperature. As the oil cools less water is held in solution, and more in suspension. I do not believe that moisture in one form will have the same effect as moisture in the other, so I feel that before consistent results can be obtained the total amount of moisture the oil contains and the temperature must be controlled and recorded.

If oil contains moisture in suspension it appears difficult to reproduce results because each successive shot draws more moisture into the gap. The reason is self-evident. Water has a higher dielectric constant than oil and so is impelled into the region where the electrical stress is greatest.

In our tests a number of sludged samples of oil were found, which had relatively high breakdown strengths when tested on a short chopped wave; and relatively low strengths when tested at 60 cycles in the standard gap. The power factor of these sludged samples was high.

I wonder if Professor Sorensen does not emphasize too much the advantages of constructing a tank of Herkolite or some other material which has a dielectric constant about the same as oil. It is true there will be little field distortion at the oil-Herkolite boundary, but very close to it is the Herkolite-air boundary, where there is a change of dielectric constant and a distortion of field.

A. E. Harrison (California Institute of Technology, Pasadena): A diagram showing the time of application of surges to the one-inch electrodes at four-inch spacing has been prepared to illustrate the phenomenon of application of crest voltages above the probable minimum value without breakdown. Figure 1 of this discussion shows two runs made July 18 and July 19, 1938. The ordinates of the points represent crest voltages, while the time in hours gives the intervals of time between application of surges. The figures above certain points give the breakdown time in microseconds. No breakdown occurred for surges indicated by open circles.

I interpret these data as follows: Application of surge voltage less than that required for breakdown changes the condition of the electrode surface, and/or the condition of the oil so that the gap will not break down when the probable minimum value of crest voltage is exceeded. The influence of operating procedure has not been established, although recent evidence points to the conclusion that the stirring of the oil after breakdown has occurred may account for this behavior. Stirring the oil when breakdown had not occurred, and waiting 15 minutes (the next to last point on July 19 and other similar tests not illustrated) would not cause breakdown to occur, however. Once breakdown has occurred at a high voltage, breakdown will then occur at the probable minimum voltage. (Note point at time two hours on July 19.)

This unusual behavior was quite consistent on days when it occurred, but there were times when the phenomenon failed to occur for no apparent reason. Also, this phenomenon did not seem to occur when the oil around the gap was not stirred after a breakdown, although failure to stir the oil seemed to reduce the strength of the oil in

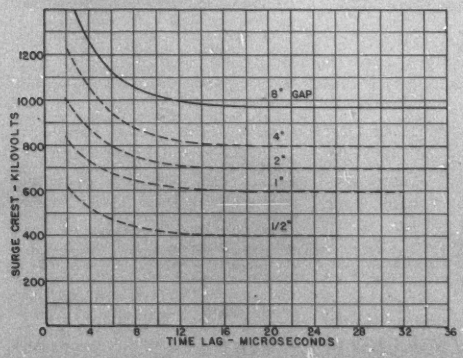


Figure 2. Time-lag curves for one-inch electrodes with hemispherical ends, 1½ x 40-microsecond negative impulse wave

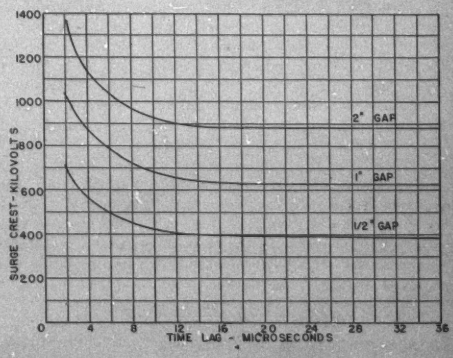


Figure 3. Time-lag curves for two-inch electrodes with hemispherical ends, 1½ x 40-microsecond negative impulse wave

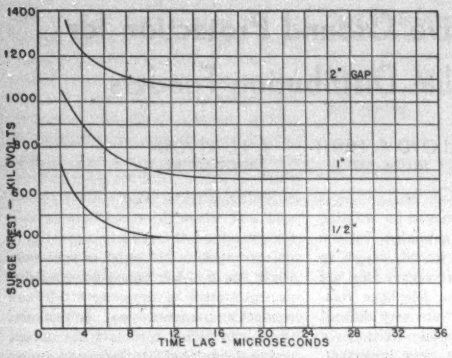


Figure 4. Time-lag curves for four-inch electrodes with hemispherical ends, 1½ x 40-microsecond negative impulse wave

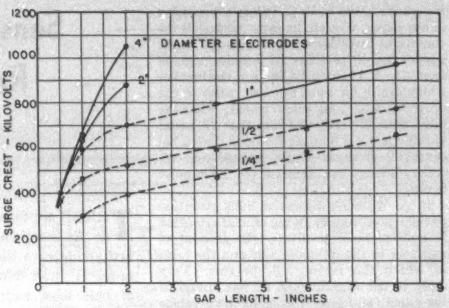


Figure 5. Curves showing relation of gap length to minimum surge crest voltage required for breakdown between cylindrical electrodes one-fourth-inch, one-half-inch, one-inch, two-inch, and four-inch diameter, with hemispherical ends, the gaps being immersed in transformer oil and subjected to 1½ x 40-microsecond negative impulse waves

some cases. We would be interested in hearing possible explanations of this unusual behavior.

A. Lovoff (California Institute of Technology, Pasadena): I would like to present additional data on the breakdown characteristics of oil, obtained in the high-voltage laboratory of the California Institute of Technology subsequent to the writing of Doctor Sorensen's paper.

Figures 2, 3, and 5 of this discussion show an extension of the data for the one- and two-inch electrodes and figures 4 and 5 show data for the four-inch electrode not included in the paper. The dotted curves are the same as those presented by Doctor Sorensen in his paper and are reproduced in this discussion for the sake of completeness. The curves of figure 5 and a curve for point electrodes if all plotted on one log-log plot will show for the larger gap spacings the manner in which the curves for the various-diameter electrodes approach the needle-gap curve. Such a log-log plot will be included in a paper now in preparation, hence will not be given in this discussion.

Recent preliminary power-frequency-voltage breakdown tests on these electrodes to determine the one-minute hold voltage disclose that the ratio of minimum surge breakdown voltage to the one-minute-hold power-frequency voltage (crest) is approximately 2.2. This impulse ratio of 2.2 checks with the figure given by Doctor Sorensen.

The anomaly of the application of greater than the established minimum breakdown surge voltages without oil breakdown occurring, as discussed by A. E. Harrison, may possibly be explained as follows. After the oil has been broken down in the gap and the oil stirred, a high enough concentration of carbon particles might remain in the vicinity of the gap to distort the field in such a way as to increase the breakdown voltage. I have noticed this failure-to-breakdown phenomena at higher than the established minimum surge voltage when testing the one-inch electrodes at the four- and eight-inch spacings. In that case the oil after being subject to several successive shots at higher than the probable minimum breakdown surge voltage without a resulting oil breakdown was restored to a normal breakdown status by proceeding as follows: the oil was very thoroughly stirred and after a ten-minute wait subjected to a surge voltage just above the probable minimum, when it was found to resume a normal performance. Three such instances noted in my records tend to substantiate the contention that foreign matter introduced during breakdown is the cause of this no-breakdown phenomena at voltage values higher than the probable minimum surge breakdown voltage.

Royal W. Sorensen: Mr. Montsinger's comments are valuable additions to the bit of information regarding surge-voltage performance for electrical conductors in oil included in this paper, which we hope has initiated a program of testing that will give us a more extensive knowledge of surge voltage performance.

All of the statements in our papers do not seem to convey to Mr. Montsinger the same meaning as that which we intended. Our reason for using rods with hemispherical ends as electrodes was not to simulate the conductors in circuit breakers, because circuit breakers do not use electrodes of that shape. The electrode shape we used was chosen because the sphere gap is a standard method of making voltage measurements. Spheres in oil with supporting shanks of small diameter, however, are more susceptible to shank influences than are similar spheres in air. Hence to avoid possible variations in arc-over voltage due to differences in shank sizes which might be used, rod electrodes with the ends rounded off as hemispheres were used.

Subsequent to the writing of the paper under discussion, we have made tests which have given us much data not available for the paper. Some of these additional data are recorded in the curves of figure 5 of Mr. Lovoff's discussion. It is interesting to note that the extended curves including these additional data are satisfactorily in accord with the curves of the paper's figure 8, to which Mr. Montsinger has referred. It is true that for the larger spacings, as Mr. Montsinger has pointed out, not only the one-inch-diameter electrode, but also the other electrodes show smaller increases in voltage breakdown values as the spacings are increased. When, however, we can obtain a high enough voltage to get out on the straight-line parts of the curves, as has been done for the one-fourth-, one-half-, and one-inch electrodes, it is interesting to note that the curves are approximately parallel when plotted on rectangular co-ordinate paper, as is the case for figure 8 of the paper under discussion, and figure 4 of Mr. Lovoff's discussion.

Mr. Montsinger states that "generally when spheres are used with spacings several times their diameter, they act like sharp-cornered electrodes so far as breakdown versus spacing is concerned." Some of our data, not yet published, bear this out, because for all electrodes when the spacing is sufficiently increased, we find that the curves of breakdown voltage versus gap length for the electrodes approach the point-gap curve.

Mr. Montsinger calls attention to the fact that he has available "a large amount of data on breakdown of oil for square-edged and round rods (both parallel and at right angles) and (that) in all cases the breakdown is roughly proportional to the spacing raised to the two-third power." I presume he refers specifically to surge-voltage breakdown. I would be interested in seeing these data, not only to note what the surge breakdown values are, but also to note whether parallel and crossed rods for surge voltages have (as is the case with power-frequency voltages) the same breakdown values for parallel and crossed rods, a fact long ago noted in Schwaiger's "Theory of Dielectrics."

Mr. Montsinger also states that for limited spacings up to six or eight inches the voltage increases slowly with spacing. Also an inspection of the curves shows that with such spacings tests on electrodes having diameters of one inch or less give for these spacings curves that are approximately straight lines. I cannot, however, give any information as to what circuit-breaker engineers find for the kind of electrodes used in circuit breakers because I have not seen any published data for such tests. The reason for the small amount of such data available

is perhaps found in D. C. Prince's discussion of our paper, wherein he says "under all the conditions investigated (and reported in the paper) the oil presents an impulse ratio of from 2 to 3, whereas the parts of the breaker which are in air have impulse ratios of the order of 1.2." In other words, what we have done is verify the fact that oil under impulse is not a limiting factor in design because oil strength under normal and recovery voltage has taken care of the impulse factor.

E. A. Walker's discussion calls attention to the importance of giving careful attention in making these studies to the amount of moisture in the oil under test and the form in which the moisture is present. Very early in our experiments, as was stated in the paper, we found that breakdown values were very sensitive to the oil moisture content. So far we have simply avoided most of the difficulties of variability due to this moisture content by using only oil of high dielectric test; for example, oil which would stand 30,000 to 40,000 volts when tested with a standard 0.1-inch oil testing gap. In fact, as Mr. Walker suggests, there is no doubt a fertile field for investigation to determine the exact quantitative influence of water content and also of temperature on surge-voltage-breakdown values for oil.

I do not think, as Mr. Walker has stated, that we have at all overemphasized the advantages of using a test tank of material which has a dielectric constant approximately the same as that of oil, because after all the prime reason for the use of a tank made of insulation material rather than metal is the avoidance of the difficult lead-in bushing problem and the use of the large amount of oil required when steel tanks are used. The fact that the dielectric constant of the insulation material used is so nearly the same value as the constant for transformer oil and that the dielectric constants for both the oil and the insulation material is only two to three times the constant for air, is a happy coincidence which makes our plan practical; whereas it would not be so good if we had to use a barrel made of some material such as porcelain, which has a much higher dielectric constant than the material of which our test barrel is made.

At present I have no explanation for the phenomena described in Mr. Harrison's discussion and can only confine my remarks to expressing appreciation of the large amount of careful, conscientious work which he has done in obtaining for me much of the data used in this paper.

Mr. Lovoff also has added to the paper data which he has obtained and which extend the curves used in the paper to values beyond those available at the time the paper was written. To him and to other students who have helped in this work, I am deeply indebted, for without their help the large amount of testing necessary to produce this report could not have been obtained. In fact, like most research work of today, the results presented in this paper are available only because of much co-operation by many persons and it would certainly be unfair to close our discussion without expressing appreciation to the Kelman Electric and Manufacturing Company, which provided much of the equipment used in making the tests, and to Messrs. Kelman, Sadler, and Thompson, who contributed valuable suggestions.

Sensitive Ground Protection for Radial Distribution Feeders

LLOYD F. HUNT
FELLOW AIEE

J. H. VIVIAN
ASSOCIATE AIEE

THERE are three reasons for isolating or de-energizing grounded feeders: first, danger to life; second, danger to property; and third, to permit joint use of pole lines with the telephone companies. The first two are very difficult to evaluate, but in certain territories a means of isolation is very important. The third reason can be given a definite value, and the economies resulting from joint use of pole lines can more than justify this proposed scheme of sensitive ground protection for radial feeders.

This paper will not discuss the merits of leaving a ground-faulted feeder in service for the continuity of service, as may be the practice by some utilities, but discusses the methods of clearing ground faults that may normally occur on radial feeders.

Ground Faults

The magnitude of ground currents on lower-voltage feeders with solidly grounded neutral transformers varies more according to the contact resistance of the fault than it does for the location of the fault. This effect is greater, the lower the voltage of the circuit.[1] The usual voltages used for radial feeders range from 2.3 kv to 22 kv.

Many ground tests have been made on 2.3-, 4-, 7-, 11-, and 16.5-kv systems of the Southern California Edison Company, Ltd. These tests all have shown conclusively that the contact resistance has a controlling influence on the magnitude of ground current.

Tests on a 4-kv solidly grounded neutral circuit show very small amounts of current when bare wire is ground-faulted as follows: In dust 0.3 to 0.6 amperes, in grass 1 to 3 amperes, in muddy water 25 to 30 amperes. Other tests on 4 kv on dry pavement and dry sand soil, where there had been no rain for several months, show that practically no current flows. A series of tests were made on a 7-kv impedance-grounded neutral system by dropping a 2/0 bare conductor on a green lawn. In this case, with about 20 feet in contact, the current was in the order of 2 to 3 amperes during the few minutes of each test. In another test, with a ground connected to a five-gallon can in mud, 35 amperes flowed in an 11-kv solidly grounded neutral circuit. Tests were made on 16.5-kv solidly grounded neutral circuit by dropping a partial span in a dry stubble field. It was necessary for the conductor to touch a green weed or come in contact with a conducting portion of earth before current would flow. Some of the times the conductor would lie in this stubble field as if dead; then all of a sudden a breakdown to earth would occur which was sufficient to cause current to flow. From this particular group of tests it seemed as though at certain times, when the conductor was dropped, it would break down,

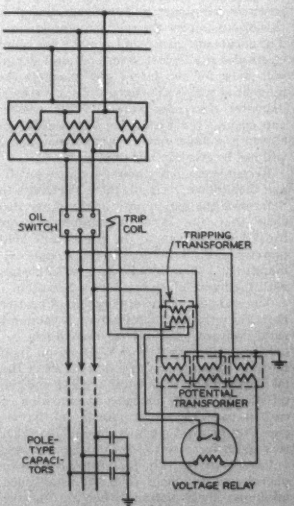


Figure 1. Sensitive ground protection for single-circuit delta system

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LLOYD F. HUNT is protection engineer and J. H. VIVIAN is technical assistant and superintendent of relays, Southern California Edison Company, Ltd., Los Angeles.

1. For numbered reference, see end of paper.

and at other times it would not. It seemed to be a critical voltage where, when in contact with earth, a breakdown would occur. It can be conceived that there is a breakdown phenomenon that is governed by voltage, current, and size of conductor, or area of actual contact surface with earth. That is, there is, under a given condition, with a conductor on dry earth, a value where practically no current flows, but by raising the voltage to a critical value, a breakdown occurs, causing current to flow. There may be a variation of this point, but it will be safe to say that the lower the voltage, the more often the breakdown will fail to occur, and the higher the voltage, the more often the breakdown will occur.

From past experience, this critical voltage under normal operating conditions seems to be between 11 kv and 22 kv. Of course, there are exceptions both ways. In other words, there are times when an 11-kv circuit breaks down, and there have been times when a 33-kv line has apparently failed to break down.

This subject of breakdown is of sufficient importance to warrant some research so that engineers, as a whole, would have a common understanding of earth faults.

With this study in mind, showing that it is possible to have earth faults that have practically no current and solid ground short circuits that have many thousand amperes, a method was sought for relaying the small ground faults, and at the same time means for limiting the maximum ground current to a desirable value.

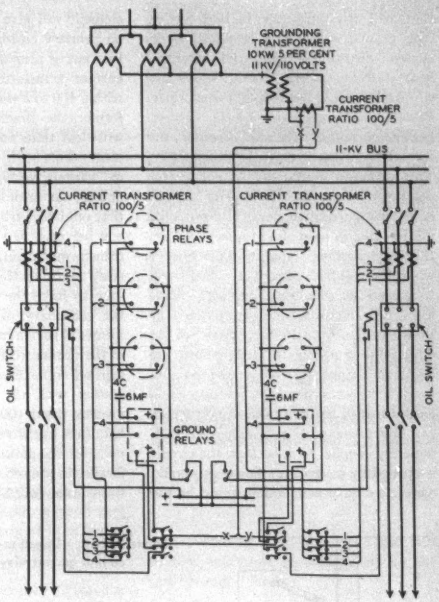


Figure 3. Sensitive ground protection for three-phase three-wire system supplying two or more feeders

In some districts where a small section is connected to a single circuit, and it is desired to clear this circuit on light ground faults, a simple scheme was devised by using an ungrounded system, and tripping was accomplished by using a voltage relay that measured zero-sequence voltage. This was tried on a 2.3-kv delta circuit approximately four miles long and proved very sensitive, using a voltage relay set at 30 volts minimum trip. In fact, when a conductor was dropped on earth or came in contact with a blade of grass, the circuit would clear without showing any signs of arcing. This scheme was too sensitive to be practical because it started tripping-out nearly every time a fog came in. In order to prevent these false operations, it was necessary to make the installation less sensitive. This was done by making the relay less sensitive; that is, giving it a higher voltage minimum trip setting, but still the operation was not satisfactory, as the leakage current from the fog was as great as the charging current from the conductors. On these circuits the smallest-size pole-type capacitors (5 kva, 2,300 volts, 60 cycles) were added at the end of the three-phase line. These three capacitors, each connected between one phase wire and ground, are sufficient to stabilize the neutral or ground point under normal conditions. By placing the capacitors at the end of the line, an added feature was accomplished; that being open-circuit protection. Should any phase wire open between the transformer bank and capacitor, the zero-sequence voltage would be sufficient to operate the relay.

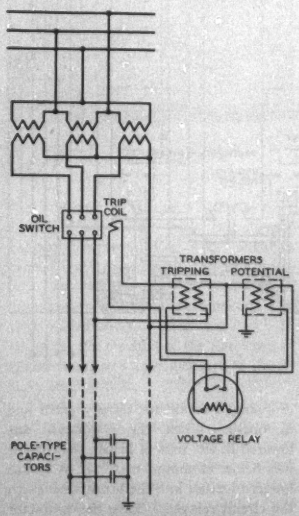


Figure 2. Sensitive ground protection for single-circuit four-wire star system

Figure 1 gives a typical connection for this scheme. With the relay set at 30 volts, the grounded feeder would have to cause about 0.5 ampere to flow; so, with this arrangement, the minimum trip would occur with approximately a 2,000-ohm fault.

Figure 2 gives a method of obtaining this protection on a four-wire system. In this case, all the grounds must be kept off the neutral wire. The minimum trip of the relay is approximately 20 volts.

In these two schemes, the use of the capacitors gives the circuit a small amount of reactive kilovolt-amperes, which is generally beneficial.

If the above scheme is used when two or more feeders are supplied from a bus, there is no method of giving feeder selection so it must be arranged to trip all feeders. If selection is required, it may be accomplished by the following method:

Figure 3 is a scheme for a three-phase three-wire system supplying two feeders

that will trip only the faulted feeder. The ground relay is a standard overcurrent directional type. The overcurrent elements of all ground relays are supplied from a grounding transformer. With a ground occurring on this system, heavy currents circulate through the secondary of the grounding transformer. This gives an abundance of energy for supplying the high volt-ampere burdens of the overcurrent elements of directional relays. So, in case of a grounded feeder, this transformer supplies this energy while the residual current is called upon to operate the directional contact. Since the relay is directional controlled, as shown in figure 4, it is necessary for the directional contacts to close before the overload can operate. Referring to figure 4, when current is flowing from the ground bank through the relay coil *a*, no current can flow through *b*, although it is magnetically coupled to *a*, because the circuit is opened by contacts *c*; however, should contacts *c* be closed, which would be the

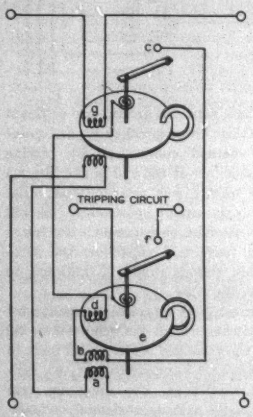


Figure 4 (left). Direction-control ground relay

case should the ground fault be on the line to which this relay is connected, then with contacts *c* closed, induced voltage from coil *b* would circulate through coil *d*. This causes rotating flux on disks *e*, closing tripping contacts *f*.

The relay used is a standard power-directional relay, and the small residual current from the line current transformers is applied to the potential coil of the directional element. A six-microfarad capacitor placed in series with the coil *g* resonates at 50 cycles and reduces the impedance of the circuit, so that the directional element will operate on a very small residual current.

In fact, from our tests, the directional element will give positive closing torque on primary currents much less than one per cent of primary rating of wound-type current transformers. This means that with a 100 to 5 wound-type current transformer, the directional element will close with less than one ampere primary current. This being the result of many tests on various voltage circuits, gave us a definite factor of safety by using the rule that minimum trip of the relays should be one per cent of the wound-type current transformer rating. In order to get the relay to trip on this value, it will be necessary to have the current transformer in the secondary of the grounding transformer of such a ratio as to give 5 amperes in the normal relay with 4- to 15-ampere taps set on the 5-ampere tap. Then, on a system with the feeder current transformers rated 100/5 and a standard distribution transformer rated 11 kv to 110 volts for the grounding bank, the current flowing in the secondary of the grounding transformer will be 100 amperes with one ampere ground. With the 100 amperes, it will be necessary to use a 100/5 current transformer in this location, as shown. With one-ampere primary-current minimum trip, a maximum current of approximately 10 amperes would make a good ratio for relaying. By neglecting the impedance of the power bank and system, it is easy to figure out the size of the grounding transformer. If we use a standard 10-kw 11-kv transformer with an impedance of five per cent, the maximum current flowing to a solid ground at the station will be 10.5 amperes. It is not essential to get exactly this value, and when a four per cent transformer is used, the maximum ground current will be approximately 13 amperes.

If the power transformer bank has a delta connection, it will be necessary to use three transformers connected star, 11 kv neutral grounded, with the secondaries connected in delta, and proper current transformer used to give the one-ampere minimum trip, and the size and impedance to give the maximum ground current of approximately ten amperes. This one-ampere minimum trip represents a fault with approximately 5,700 ohms. At our Goldtown substation, the connection is the same as figure 3, except there are three feeders instead of two. After the installation, tests were made by dropping a conductor on dry earth and in brush. When the conductor was lowered in the tops of brush, the current was below minimum trip, but as it was lowered further into the brush, near earth the circuit relayed. Then the conductor was dropped into a small tree, but was kept clear of earth. In this case no relay

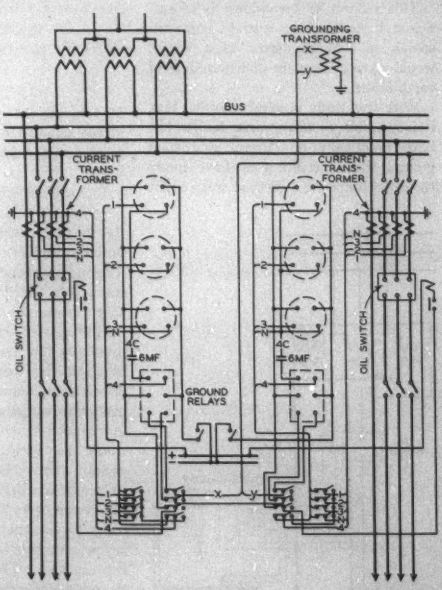


Figure 5. Sensitive ground protection for three-phase four-wire system supplying two or more feeders

action took place. The conductor was then dropped on earth in many places, either slowly or suddenly, and in every case the circuit relayed correctly. The values of ground current ranged from 2 to 8 amperes. The conductor was then solidly grounded, and the maximum current was approximately 13 amperes. The grounding transformer used at Goldtown is a 10 kw, four per cent.

Figure 5 shows the connections of a three-phase four-wire system. Since the load may be connected between one phase

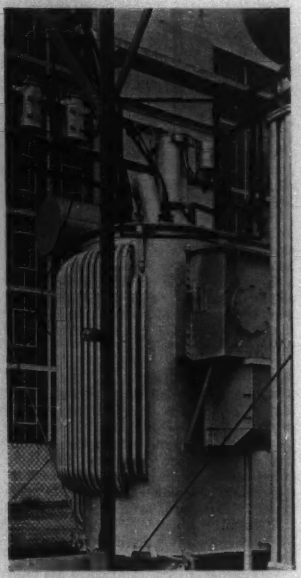


Figure 6. Grounding transformer

wire and neutral, it is very likely to have an unbalanced load with the neutral carrying current. For this sensitive ground-current system to function properly, it is necessary to have four current transformers and to have the neutral wire ungrounded and not interconnected. In this case, the residual of the four current transformers is a true measure of phase-to-ground current.

Figure 5 is similar to a four-wire four-kilovolt system installed at Topango substation. This installation was given a complete test by grounding feeders. The minimum trip was slightly less than one ampere. The bare conductor was pulled over trees with no relay operation, showing tree grounds would not cause unnecessary operations. The conductor was dropped on various kinds of soil, and relayed in most all cases except when dropped on very dry soil and on oiled pavement. Several cases where the low-voltage ohmmeter showed very high fault resistance, the circuit relayed when energized. One of these cases was a heavy retaining fence with several concrete poles connected together with several strands of heavy steel cable. The steel was not grounded, but was tied together. The low-voltage ohmmeter gave a resistance to ground for this installation of 40,000 ohms, yet when contacted by a conductor, the circuit relayed properly. This test confirms there must be some phenomenon of breakdown, as the minimum trip of this circuit was in the order of 2,000 ohms.

At Vernon City plant, there are 20 seven-kilovolt circuits equipped with this sensitive ground protection. This sensitive ground protection was installed on account of the desirability of joint use of pole lines with the telephone company. The normal minimum trip of each feeder was set at 600 amperes and with the possibility of several thousand amperes maximum ground fault current. With the sensitive ground protection in with 400/5 wound-type current transformers, the minimum trip is 4 amperes, and the maximum ground fault current is 40 amperes. Figure 6 shows the 20-kw, four per cent transformer used for the grounding transformer at the Vernon City plant. Figure 7 shows the installation of eight sets of feeder relays at this station; the four upper relays are the ground relays, while the corresponding three-phase overcurrent relays are directly below.

Line-dropping tests of this installation proved to be as designed; that is, the directional element gave definite operating torque on only the faulted feeder at about one-half minimum trip of four amperes, with a maximum of 38 amperes ground current.

This system of ground protection has been in operation for several years, and no unnecessary trip-outs have occurred, and many necessary trip-outs have occurred correctly. When phase-to-ground faults occur on this system, the customary voltage drop does not occur, due to the small amount of ground current flowing.

In fact, this system has proved so successful that several other installations are being made this year. Also, a system will be worked out using this principle for isolation of loop feeders during the year. At present there seems to be no means of adequately isolating phase-to-ground faults on distribution loops or interconnected systems. So, it is hoped that this system will prove as satisfactory as the one for radial feeders.

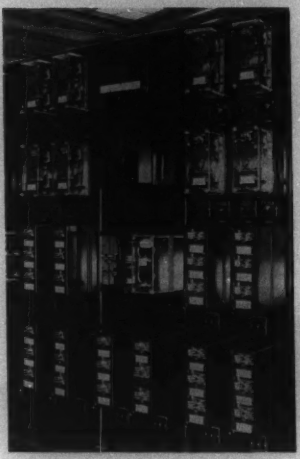


Figure 7. Ground-relay installation

Reference

1. Some Recent Relay Developments, Lloyd F. Hunt and A. A. Kroneberg. Electrical Engineering (AIEE Transactions), April, 1934.

Discussion

L. F. Kennedy (General Electric Company, Schenectady, N. Y.): For many years the detection of high-impedance grounds occurring on relatively low-voltage circuits has been one of the unsolved problems. Some have thought to avoid the problem by the use of an isolated-neutral system. Messrs. Hunt and Vivian have pointed out that continued operation of an accidentally grounded circuit may constitute a danger to life and property. The authors' approach to the problem has been to provide a grounded-neutral system having relatively high neutral impedance. With such a system the effect of resistance at the point of fault is decreased and the range of current over which the protective relays must operate is considerably narrowed down. If the working range is relatively small, it will be easier to provide a protective relay system which may be more generally relied upon to detect faults. In general, it may be said that the authors are proposing a system having a maximum zero-sequence current of the general order of ten per cent of the circuit rating. With this system they propose a relay sensitivity of one per cent. Such an operating range of the order of ten to one is not particularly difficult to obtain with existing relay designs. The greatest difficulty lies in obtaining a relay which will

actually operate at one per cent of the circuit-rating primary values. The circuit arrangement used by the authors obtains the main energy required for the operation of the relay system not from the line current transformers but from the current transformers carrying only the ground current. In this way the difficulty of obtaining very sensitive operation is overcome.

In other words, the authors are using standard equipment with impedances coordinated with the circuit rating and a modified system of relay connections. They have furthermore differentiated between the various types of circuits used for distribution service and apply solutions all of the same general class, but specifically adopted to each type of service.

In the early part of the paper under the heading "Ground Faults," the authors quote figures on various tests which were made under grounding conditions where relatively small currents were measured. The value of these test figures would be much greater if they were presented together with the actual constants of the circuit on which the tests were made. The general statements as to the amount of current which might flow through various types of soil would be of much greater value if related directly to maximum currents which would be encountered with a fault having zero resistance. More data of this type, together with a résumé of operating experience as times goes on, would be greatly appreciated by all who are interested in the solution of this particular problem.

Wm. R. Brownlee (The Commonwealth and Southern Corporation, Jackson, Mich.): In view of the tremendous increase in common-neutral distribution construction during the past six or eight years, it is unfortunate that the various methods of sensitive ground protection described by the authors are not recommended except for delta circuits or four-wire circuits with individual neutral wires grounded at the supply substation only. Many schemes have been available for years for securing sensitive ground protection on delta or unigrounded systems. However, the choice of sensitivity is practically always a compromise between conflicting requirements so that in the vast majority of installations, relay settings are less sensitive than the minimum which is readily available with standard equipment.

The authors are to be congratulated on the ingenious use of distribution transformers and current transformers, which are normally carried in stock, as a makeshift arrangement for securing a neutral reactor of some 600 ohms and a very low ratio or even step-up current transformer. If, after further experience, they should decide that they wish to maintain the extreme sensitivity and rather low upper limit of fault current, it might be well to investigate the cost of simple neutral reactors and step-up current transformers which might be less than that of the distribution transformer combination, even though the latter is a quantity-production unit.

Many methods are generally available for securing sensitivity on the order of one ampere primary as recommended by the authors. For single circuits, a standard 5/5-ampere neutral-current transformer may be used with a standard 0.5- to 2.5-ampere relay. For a simple residual connection, standard relays are available with a minimum rating of 0.1 ampere with which a pick-up of one ampere primary can be secured with line current transformers up to 50/5 amperes which would ordinarily be associated with a 1,000-kva circuit at 11 kv. Another common method is the use of a current-polarized directional ground relay having most of its volt-ampere burden concentrated in the coil supplied from the neutral current transformer, permitting low current settings even on circuits above 15 kv where bushing current transformers are frequently used. With instrument-type current transformers, the low burden of such a relay permits the use of a step-up current transformer for the current supplied from the residual of three line current transformers, allowing most any desired sensitivity to be obtained with standard relays.

Where special considerations may warrant extreme sensitivity, an arrangement was described in 1933[1] for responding to grounds with as much as 5,000 ohms resistance on a 2.3-kv three-phase circuit. The measured values in a variety of conditions at this voltage varied from 60 ohms to 3,300 ohms at point of contact.

The use of neutral impedance in limiting ground current has been widely discussed.[2] It is felt that the maximum value of ten amperes recommended by the authors is far too low for the usual conditions to give any appreciable consideration to the selectivity of branched fuses, individual distribution transformer fuses, or the ability to clear defective lightning arresters from the line or even to cause sufficient damage on them (or on other defective apparatus) to permit locating and clearing permanent trouble in any reasonable length of time. With these considerations in mind, the maximum current should probably be not less than 50 to 100 amperes.

Undoubtedly the schemes of the authors are useful in combating local conditions. They are faced with unfortunate California weather conditions, such as extreme drought resulting in heavy layers of dust contrasted with the occurrence of fogs sufficiently dense to short circuit the charging current on one conductor of a circuit.

REFERENCES

1. ZERO-SEQUENCE CURRENT TRANSFORMERS FOR GROUND PROTECTION, J. W. Graff, *Electrical World*, December 23, 1933, page 82.

2. GENERAL CONSIDERATIONS IN THE USE OF NEUTRAL IMPEDANCE, EEI Publication No. *D*-14.

P. E. Benner (General Electric Company, Schenectady, N. Y.): The authors are to be congratulated on their analysis and solution of the problem of de-energizing of grounded conductors. With the stretching out of circuits to pick up scattered loads, situations involving this problem of fault protection are apt to turn up on any system. There is also an increasing appreciation of the necessity for providing a means of de-energizing grounded or faulted conductors to minimize possible danger to life and property.

The common-neutral multigrounded system depends on short-circuit currents for de-energizing grounded conductors and in this way is dependent to a large degree on low ground impedance for successful operation. Unfortunately, as the authors point out, the ground and contact resistance may be almost anything with the result that de-energizing grounded feeders is somewhat uncertain with this type of protection.

In a common-neutral multigrounded system where sufficient ground current is obtained in the case of grounded conductor to cause the operation of a sectionalizing device or the substation breaker, this method of protection might possibly have the advantage of confining the outage to a fewer number of customers; however, it is doubtful whether this advantage would offset the more positive operation of the protective scheme described by the authors. In this connection it probably would not be entirely unexpected if the de-energizing of grounded feeders assumed a greater importance in future layouts than first cost or service reliability because of the fact, as mentioned by the authors, that it involves the question of danger to life and property.

In urban areas where water-pipe grounds are available, the common-neutral multigrounded systems would probably be entirely effective in isolating grounded feeders. Just how effective the multigrounded common-neutral system is for isolating grounded feeders in rural areas will unquestionably be determined in the next few years by the experience with the many miles of this type of circuit which have been recently installed. In any event, it is believed it will be advisable to keep a close check on this phase of circuit operation so that proper value can be placed on this question of providing for the de-energizing of grounded feeders on future circuits.

Frederick C. Lindvall (California Institute of Technology, Pasadena): The need for sensitive ground protection is brought out by Messrs. Hunt and Vivian through examples of peculiar grounding conditions experienced on the Southern California Edison system. In these examples the ground current either failed to flow altogether, or else was of much smaller magnitude than would have been predicted on the basis of ordinary resistivity measurements.

Verification of these experiences has been made at the California Institute of Technology both with samples of earth brought into the laboratory for study and with actual high-voltage grounds in soil outside the high-voltage laboratory.

It was found that a wire or small electrode lying on the surface of moderately dry ground could be held at a potential of 10,000 to 15,000 volts without breakdown or flow of appreciable ground current. Actual ground current flow was found to be the result of a breakdown of the soil quite similar to that of dielectric failure. Broadly summarized, the results indicate that dry to moderately dry soil should be regarded more nearly as a poor dielectric material than as a substance of definite resistivity. The laboratory studies indicated that moisture content of the soil, its composition, and the mode of contact of the electrode all have a bearing on the subsequent breakdown and flow of ground current. The wide variation of the results points to the desirability of field studies comparable with actual operating conditions rather than an intensive laboratory study of the dielectric behavior

of soils, although such investigation would offer results of considerable academic interest.

Our conclusion is that a careful study of grounding conditions should be made, as the results of Hunt's and Vivian's work, together with the laboratory studies which we have made, indicate considerable uncertainty in the technique of grounds, both deliberate and accidental.

J. R. North (The Commonwealth and Southern Corporation, Jackson, Mich.): This paper describes a unique method of obtaining sensitive ground relaying on three-phase delta (ungrounded) circuits or three-phase unigrounded circuits. This method of very sensitive relaying is no doubt advantageous, as described by the authors, in areas where the fault energy and duration must be held to extremely low values.

In the introduction, it is stated that one of the reasons for providing ground relaying on distribution circuits is "to permit joint use of pole lines with the telephone companies." It is difficult to understand just why such sensitive ground relaying is required for joint use with low-voltage distribution circuits, since there are many thousands of miles of jointly used pole lines throughout the country now operating apparently satisfactorily with distribution circuits which are not provided with ground relaying.

In the case of high-voltage joint use, detailed studies have indicated that the conditions as far as the power circuits are concerned would be properly met if the circuits are promptly de-energized in, say, five seconds or less with fault currents of the order of 50 amperes or more. Contacts with communication circuits generally result in values of fault impedance far less than in the case of a contact with dry dust and thus ample current would be available for operating ground relays or blowing fuses.

M. A. Sawyer (Southern California Telephone Company, Los Angeles): The methods of obtaining sensitive ground protection on radial distribution feeders described by Messrs. Hunt and Vivian appear to be admirably suited for use in situations involving the joint use of poles by higher-voltage power distribution circuits and communication facilities. As has been pointed out in a previous paper ("Protection Features for the Joint Use of Wood Poles Carrying Communication Circuits and Power Distribution Circuits Above 5,000 Volts," J. O'R. Coleman and A. H. Schirmer, AIEE TRANSACTIONS, March 1938), safety in joint use is dependent largely on the following factors:

1. Frequency of occurrence of contacts between power and telephone circuits.
2. Voltage on the telephone plant when contact occurs.
3. Current in the telephone plant when contact occurs.
4. Duration of contact.

The first factor is, of course, in many respects a function of the mechanical design, construction, and maintenance of the line and depends somewhat on the type of plant, tree conditions, exposure to traffic, or other hazards rather than the electrical characteristics or protective devices. The other three factors are, however, controlled to a large extent by the system of sensitive ground protection described in the paper. In addition to providing a means of promptly de-energizing the feeder in case of accidental contact with telephone plant, the voltages and currents impressed on the

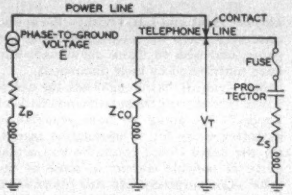


Figure 1. Fault circuit of a power-line contact with telephone plant

telephone plant are minimized by virtue of the large amount of impedance introduced in the power system by the grounding transformer.

The voltage on the telephone plant in case of contact is dependent on the power-circuit voltage and the ratio of the impedance in the telephone plant between the point of contact and ground to the total impedance of the fault circuit. Referring to figure 1 of this discussion which shows in schematic form the fault circuit of a grounded-neutral system, it will be noted that the voltage on the telephone plant (V_t) is $E\frac{Z_t}{Z_t+Z_p}$ where Z_t is the parallel impedance of the two paths to ground. The current in the telephone plant is $\frac{E}{Z_t+Z_p}$ and divides over the two paths inversely in proportion to the impedance of the paths. If the telephone fuse opens, the voltage across the fuse and on the telephone plant then becomes $E\frac{Z_{co}}{Z_{co}+Z_p}$ and the current is $\frac{E}{Z_{co}+Z_p}$. If the telephone fuse opens and the connection toward the central office is lost at the point of contact, the voltage across the fuse and on the telephone plant then becomes E. Since the current under these conditions becomes zero, the power circuit would not be de-energized and this voltage would remain on the telephone plant unless it was large enough to break down the insulation at some point.

Since the sensitive ground protection system for use on higher-voltage feeders employs a grounding transformer in the neutral the impedance of the power system (Z_p) is increased by an amount equal to the impedance of this transformer. If, for example, a ten-kilowatt 11-kv grounding transformer of five per cent impedance is used the added impedance would be approximately 605 ohms. This would limit the fault current that could flow into the telephone plant in case of contact to a maximum of about 10.5 amperes assuming $Z_t=0$ and neglecting the impedance of the power feeder. If it is also assumed that the impedances of the two paths to ground in the telephone plant are $Z_{co}=200$ ohms and $Z_t=50$ ohms (resistance) and again neglecting the impedance of the power feeder the total current would still be approximately 10.5 amperes and the voltage on the telephone plant would be about 420 volts. If the telephone fuse operates the current would be reduced to about 10 amperes and the voltage on the telephone plant would increase to approximately 2,000 volts. If in this case the minimum trip current of the feeder ground relay is 2 amperes it is quite probable that the circuit will be de-energized before the telephone fuse will operate.

Where the telephone plant is cable the impedance to ground (Z_{co}) will normally be very small as compared to the impedance of the grounding transformer. A contact with the cable will therefore impress a relatively low voltage on the telephone plant, well within the range that can be handled by the telephone protector. Furthermore, with the small value of fault current the liability of a cable burn-off allowing the voltage on the telephone plant to rise to full phase-to-ground voltage is remote. It therefore appears that with this system of ground protection and with the normal cable sheath grounding and subscriber station protection practices employed in the telephone system, suitable protection co-ordination should be obtained where higher-voltage joint use with telephone cable is involved.

Where the telephone plant is largely aerial wire it is normally difficult to obtain protection co-ordination of the two systems because of the relatively high impedance of the telephone wire, and in many instances in rural areas low-impedance grounds are not available for the subscribers' protector. Due to the high impedance in the telephone plant the resulting voltages on the telephone plant will be high and the power system fault current may be limited to the extent that the circuit is not promptly de-energized. Furthermore, with the limited current-carrying capacity of the open wire as compared to the cable sheath and suspension strand, the possibility of burning off the wire is much greater than where cable plant is involved.

However, with the method of ground protection described in the paper the fault current may be limited to a relatively low value which in turn reduces the possibility of burning off the telephone open wire. Also, because of the impedance of the grounding transformer the impedance to ground of the telephone plant may be somewhat higher than would otherwise be permissible without impressing an excessive voltage on the telephone plant at the time of contact. Since the relay system may be arranged to de-energize the feeder with a fault contact resistance as high as 2,000 or 3,000 ohms it is unlikely that the impedance of the open-wire telephone plant assuming no burn-offs will prevent tripping of the circuit. With the use of auxiliary three-kilovolt protective gaps to ground in the telephone plant to limit the voltage across the fuse and to insure a continuous path to ground for the contact current, it appears that with this method of ground protection employed in the power system, protection co-ordination can often be secured in a practicable manner in open-wire joint-use situations.

While the sensitive ground protection described in the paper was originally developed to enable the tripping of distribution circuits involved in ground faults of high con-

tact resistance it would appear to also offer a practicable means of providing the necessary degree of safety in many situations in which higher voltage joint use is the best solution. The authors are to be complimented on their development of this system and its application as described in the paper.

R. M. Smith (Westinghouse Electric and Manufacturing Company, Newark, N. J.): Mr. Hunt and Mr. Vivian are to be congratulated on the amount of field development work that they have done on this problem. The solution which they offer is certainly a simple one and from their records it appears that a sensitive-type ground protection has been achieved without incurring unnecessary trip-outs. It would be desirable to hear from other relay engineers in different parts of the country with respect to their experience in attempting to achieve a sensitive type of protection.

A recent investigation undertaken by the writer indicated that although a few attempts had been made to obtain ground-fault relaying on distribution feeders with a sensitivity as low as 5 amperes primary, the general trend was toward considerably higher currents usually with a minimum of 50 amperes. The writer believes that the danger of unnecessary trip-outs due to tree grounds has been greatly exaggerated and that no real concrete data exist as to the extent of the hazard. It is unfortunate that the novel solution offered by Messrs. Hunt and Vivian is applicable only to distribution systems operating with a single ground. The general tendency at the present time appears to be in the opposite direction; that is, multiple grounds. Perhaps it might be well for the industry to again evaluate the many factors that are involved in single versus multiple grounding and reverse this trend, if the advantages of a sensitive ground protection overweigh some of the advantages of the multiple-grounded system.

L. N. Crichton (Westinghouse Electric and Manufacturing Company, Newark, N. J.): It is my belief that this paper gives the answer to the old problem of properly protecting distribution circuits against the hazard due to fallen wires. The simplicity of the idea is unusual; it requires a standard relay and a standard distribution transformer as a grounding reactor. The requirements as laid down for proper sectionalizing are likewise simple; namely, to clear all troubles having a ground current of more than one ampere. The amount of unbalance current in the load does not enter into the problem. The method of determining the size of the ground transformer is simple and thoroughly explained in the paper.

It is to be hoped that other systems in different localities will quickly install this type of protection so as to obtain experience in parts of our country where climatic conditions are different. What we all suspect, of course, is that in most localities, tree ground currents will be a nuisance after long spells of wet weather.

Recent tests that have been made in another part of the United States indicate that tree grounds are not so likely to cause trouble as has been feared in the past. Perhaps it will be necessary to raise the minimum current to some value above the one ampere set by the authors, but the practical value may not be more than two, three, or four amperes. I am confident that the limit will be a low one and hope that the industry will soon discover what it is by a number of trials of this new scheme.

Lloyd F. Hunt and J. H. Vivian: We appreciate very much the interest shown in our paper, and wish to thank our friends who have contributed by their discussions.

Mr. Kennedy has brought out the necessity of having more information on "Ground Faults." We admit we have been lax in gathering every bit of information regarding the detail circuit constants and actual range of possible current in some of the tests. We purposely left this information brief for two reasons: first, it only applies to our conditions; and second, as Doctor Lindvall has brought out in his discussion, a very great deal is not known about earth faults and earth contact resistances, so we feel that this subject is important enough to have considerable more work done on it and a paper written covering the results; Mr. Kennedy also brings out the desirability of having operating experience. To date our operation has been all correct. However, with more experience and with this type of protection in more varied localities, it will be possible to give valuable information on its operating record.

Mr. Benner brings out a very interesting part of the story of sensitive ground protection that we purposely avoided, which is the policy of de-energizing grounded feeders. Each organization has its problem in this regard, and may make its own decisions whether or not grounded feeders should be left in service.

It is our desire to have sufficient installations to determine by experience how far we can justify this type of protection. We are now cutting over one urban territory, from 2.3 kv delta to 4 kv four-wire, to this type of sensitive ground protection. The normal change would be to 4 kv four-wire multigrounded neutral system; however, with this change it will be possible to gather interesting operating experience.

We feel, as Mr. Benner does, that with the many miles of rural lines now being put into use, more consideration should be given this problem of de-energizing them in the case of grounded conditions.

Mr. Brownlee has reviewed the prior methods of sensitive ground protection, but in his treatise no attempt has been shown to limit the ground current, which feature we feel is very desirable. In his case of using a 5/5 current transformer with one ampere tap relay, if solidly grounded on a 3,000-kva single 11-kv circuit, the relay would have approximately one ampere minimum trip, but also would give approximately 500 amperes maximum current, or a range of 500 to 1. Most every relay engineer will recognize that this range is impossible. This is more or less true in other examples brought out by Mr. Brownlee. If his method were used on the 7-kv system mentioned in the paper, it would have a minimum trip of approximately 55 amperes. This would make it necessary to use a very much more expensive joint pole construction. The saving from using the simpler construction would many times pay for the installation of our type of ground protection.

In this day of changes, the relay engineers are finally "evoluting" to a place where they can use some standard equipment, such as standard transformers for makeshift (manufacturers please note) grounding bank. All of this equipment is usable material, should further changes be made. If our present 600-ampere grounding banks were composed of standard distribution transformers instead of zig-zag, we could get some use out of them now instead of placing them in the discard. Therefore, from these experiences, we feel it is much better to use standard devices that can later be used for other purposes.

Mr. North has brought out the question of joint use with the telephone companies. We wish to bring out again that this system was developed for other reasons than joint use, but when we were confronted with joint use, especially on higher voltages, these systems of protection were available, and allowed us to use a much cheaper construction than normally used for this service, the saving being more than adequate to justify its use.

Doctor Lindvall and his associates have started a very important phase of this work of determining the phenomena regarding earth contact resistance and breakdown value. We hope he may continue his investigations, which will give us all much valuable information.

Mr. Sawyer's discussion gives in detail the advantages of our type of protection when used in joint pole arrangement. We feel that, by working with Mr. Sawyer on these problems, much better service can be rendered the telephone subscribers, who are also our customers, and at the same time more economical methods of distributing both services can be developed.

Mr. Smith brings out the unfortunate fact that this protection cannot be used on multigrounded systems. This is true, and the changing from multigrounded uninsulated-neutral systems would be expensive, and would cause a considerable write off of certain features of old construction. However, in the changeover mentioned before, a study is being made to establish the difference in actual relative costs when a new job is made.

Mr. Crichton has brought out the problem of tree grounds; also, Mr. Smith mentioned this subject. Dry trees will not cause this protection to operate when the very low minimum trip is used. It is possible that trees will cause actual phase-to-phase contacts by wind which will relay the line. In the case of wet trees, the earth must also be wet, so earth contacts would then be of less resistance. In this case it would be possible to design the system for higher minimum trip and, by taking advantage of the range of tap settings of the relays (normally 4 to 15 amperes), adjustments could be made as desired. We have had no experience with the relation of dry trees to wet trees, as compared to dry earth to wet earth, but it could be expected that the same degree of discrimination could be obtained during the wet seasons. In several cases our practice is to make the ground protection less sensitive during the rainy season.

Again we wish to express our appreciation to those who have taken part in this very interesting subject.

Transient and Steady-State Performance of Potential Devices

E. L. HARDER
ASSOCIATE AIEE

P. O. LANGGUTH
ASSOCIATE AIEE

C. A. WOODS, JR.
ASSOCIATE AIEE

THE increasing use of high-speed relaying with the resulting emphasis on the transient performance of potential devices has led to an extensive analysis of their performance under transient conditions. Both analytical and network-calculator methods have been developed for predetermining transient performance. Tests have been made to substantiate the methods of analysis and to show the character of the transient and extent of control in typical cases. Novel means have, likewise, been devised for presenting the steady-state performance of the device. In particular, the introduction of the equivalent circuit of the device represents an important advance in the visualization, both of the transient and steady-state performance. In this paper, after a brief description of circuit arrangements of the potential devices under discussion, the new theoretical methods are presented, followed by the substantiating test information.

Circuit Arrangements

A potential device may be energized from a condenser bushing or from a coupling capacitor, which may be represented as a capacitance potentiometer as illustrated in figure 1. The upper section is identified as the stack capacity and the lower section as the tap capacity. The intermediate point is called the tap. Both the stack and tap sections are contained within the porcelain housing of the bushing or capacitor.

Figure 1 shows three circuit arrangements of commercial devices and also illustrates required modifications in capacitor devices for use with carrier. Means are provided for neutralizing the effective series capacitance of the source by series reactance between the source and the burden. Variable reactor and capacitor are used in (*a*); transformer reactance in (*b*), (*c*), and (*d*). The circuit of figure 1*a* is used in the bushing potential device and the low-capacity capacitor potential device. Circuits (*b*) and (*d*) apply to the high-capacity high-accuracy capacitor potential device and include provision for obtaining several secondary voltages simultaneously through the use of a coordinated auxiliary transformer. Both the main and auxiliary transformer are designed to operate at a low flux density and will remain stable when subjected to flux densities in excess of four times normal. The circuit of figure 1*c* is used in the simplified capacitor potential device and is essentially one in which the capacitive and inductive reactances are not variable. The secondary voltage thus obtained is substantially in phase with line-to-ground voltage of the system. Simultaneous use of the coupling capacitor as a carrier-current channel, illustrated in (*d*), requires the addition of carrier-frequency chokes to complete the fundamental-frequency circuits and permit a series relation at carrier frequency between the carrier-current set and the transmission line.

The proper device for any particular application is selected with a view to economic as well as to performance considerations. The standard capacitor potential devices have the greatest accuracy and best performance, and the simplified capacitor potential device is lower in cost.

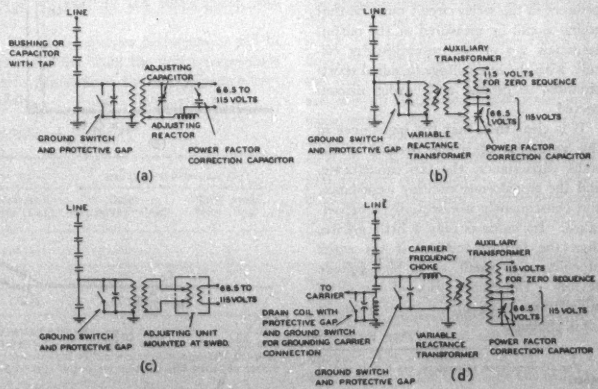
Figure 1. Circuit arrangements of potential devices

(*a*)—Bushing or capacitor device

(*b*)—High-capacity capacitor device with multiple secondary

(*c*)—Simplified capacitor device

(*d*)—High-capacity capacitor device with arrangements for carrier



Steady-State Performance

The Equivalent Circuit

The performance of a potential device may best be visualized through an understanding of its equivalent circuit, figure 2*d*. Because of the importance of a thorough understanding of this circuit in what follows, its derivation and meaning will be carefully considered at this point.

The actual circuit of a typical single-phase potential device is shown in figure 2*a*. There are many possible variations, and this particular circuit has been selected for consideration because it includes the major elements of importance and yet it is quite simple. The concepts gained from a study of it are later extended to include some of the more important variations. There is a double transformation of voltage, first through the potentiometer, formed by the "stack" and "tap" capacitances, and second through the transformer.

In figure 2*b*, the transformer is replaced by its equivalent circuit consisting of a series leakage impedance and an exciting impedance branch. The latter is almost negligible in a liberally designed transformer and the approximation of connecting it at one end of the leakage branch as shown is entirely justified. It

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E. L. Harder is central-station engineer and P. O. Langguth and C. A. Woods, Jr., are switchgear engineers, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

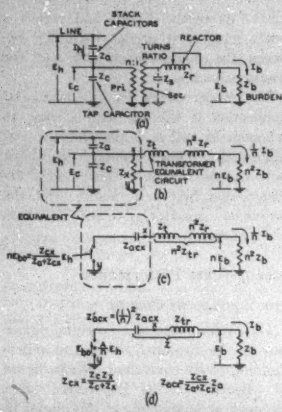


Figure 2. Actual and equivalent circuits of a device without auxiliary tuning capacity on secondary of transformer

(*a*)—Actual circuit

(*b*, *c*, *d*)—Successive equivalent circuits

may then be paralleled with the tap capacitance, and for a typical case the parallel impedance of the two is only about three per cent greater than that of the tap capacitance alone.

In figure 2*c*, the applied voltage and potentiometer circuit are replaced by a proportional applied voltage and a series impedance. This series circuit (*c*) is exactly equivalent to the potentiometer circuit (*b*) according to Thevenin's theorem of networks[5] provided the following relations are maintained. The impressed voltage in the series circuit must be the same as the voltage that would appear at the output terminals *x*-*y* on the potentiometer circuit at no load (burden disconnected). The impedance in the series circuit must be that which would be measured at the output terminals *x*-*y* of the potentiometer circuit, with the line voltage terminal short-circuited to ground and burden disconnected.

It is clear then that the impedance in the series circuit is the parallel of the stack capacitance, the tap capacitance, and the transformer exciting impedance, and consequently is essentially a capacitance. Its value is only a little greater than the tap capacitance if the stack capacitance is small, as in high-voltage devices. The combination of the series impedances in (*c*) into a single value in (*d*) is obvious.

5. For all numbered references, see list at end of paper.

If an adjusting capacitor is used on the secondary side of the transformer as shown dotted in figure 2*a*, the final equivalent circuit takes the same form (*d*). However, the values of the applied voltage and series impedance in this case are obtained by an additional transformation, using Thevenin's theorem, to take into account this capacitance (appendix I).

Performance From Vector Diagrams

The steady-state performance may now be investigated by analyzing the circuit, figure 2*d*, which is the exact equivalent of the actual potential device. Figure 3 shows a set of vector diagrams drawn for a particular device operating at rated burden. It will be observed that with unity power factor burden (figure 3*b*) the voltage across the source capacity and the inductance are equal and are approximately 80 per cent of the voltage across the burden. The voltage across the series resistance, which includes all of the device losses, amounts to 9.5 per cent of the burden voltage. From these relations, a number of interesting facts regarding the device may be deduced. The 9.5 per cent resistance drop represents the ratio regulation from no load to full load. Since the reactance drops cancel, the resistance drop constitutes the entire source voltage drop to the burden. The tap voltage, which is equal to the burden voltage added vectorially to the reactor drop, and the result multiplied by the transformer turns ratio, is higher at rated load than at no load. This is due to the fact that the reactance drops decrease to zero as the burden current is reduced to zero.

Figure 3 (*b* and *d*) also illustrates that phase-angle adjustment of the device is obtained by varying the inductive reactance. The adjustment shown in (*b*) results in zero phase angle between the high-voltage line-to-ground voltage and the burden voltage, while that in (*d*) results in a burden voltage leading by 30 degrees. The latter is obtained by decreasing the inductive-reactance drop. It is evident that with this adjustment a large phase-angle regulation as well as an increased voltage regulation results, since the voltage drop occasioned by the burden current through the complete impedance,

(*a*)—Adjustment for zero phase angle and 50 per cent leading power factor burden

(*b*)—Adjustment for zero phase angle and unity power factor burden

(*c*)—Adjustment for zero phase angle and 50 per cent lagging power factor burden

(*d*)—Adjustment for 30-degree leading phase angle, and unity power factor burden

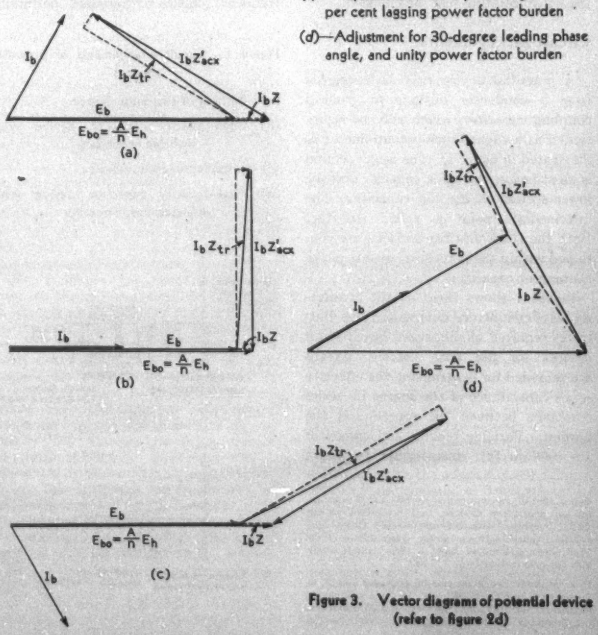
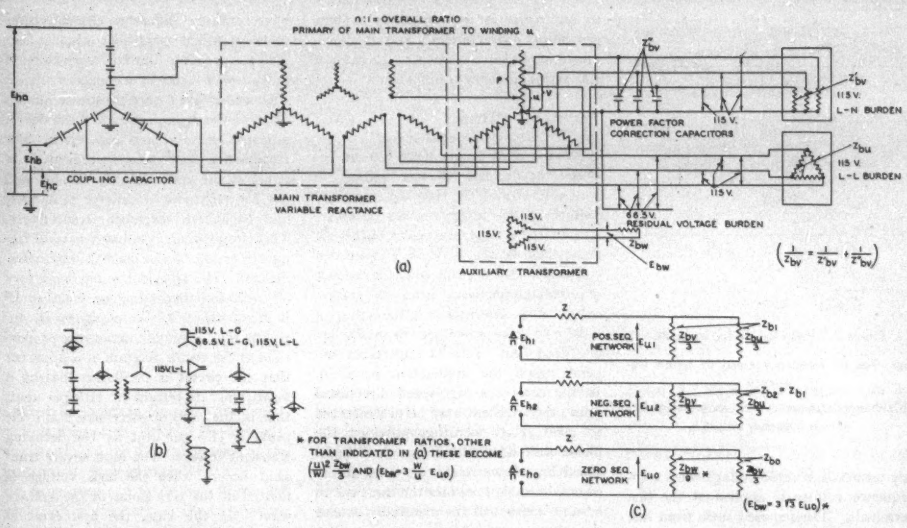


Figure 3. Vector diagrams of potential device (refer to figure 2*d*)



Z, decreased to zero as the burden current is reduced to zero. In fact, as the burden current becomes zero with normal line voltage, the phase-angle error becomes practically zero regardless of the angular adjustment of the device at rated burden.

Table I indicates the voltage performance and burden performance for various types of potential devices, while figure 10 illustrates the characteristic curves for two specific designs.

Symmetrical-Component Theory

The performance of potential devices having balanced three-phase connections operating under unbalanced line voltage conditions is best approached through the method of symmetrical components. This performance is defined as the overall ratio from high-voltage line voltage to burden voltage, and includes both magnitude and phase angle. The sequence networks for a typical device and its connected burdens are outlined in figure 4, using the equivalent circuit of the single-phase potential device previously developed.

The positive- and negative-sequence performance characteristics are the same. In either case the performance is identical with that of a single-phase device supplying a burden impedance equal to the positive- (or negative-) sequence phase-to-neutral impedance of the total three-phase burden, on the particular turns base used. Thus for all three-phase and line-to-line fault conditions, involving only positive- and negative-sequence quantities, the performance characteristics of all secondary voltages are the positive-sequence performance, and are given directly by the single-phase test data.

The zero-sequence performance will in general differ from the positive-sequence performance since the zero-sequence burden impedance is different from the positive-sequence burden impedance as illustrated in (*c*). For fault conditions involving zero-sequence the residual performance is identical with zero-sequence performance, so that single-phase tests using the burden impedances indicated in the zero-sequence network apply. The residual burden voltage is related to the zero-sequence burden voltage by the factor $\sqrt{3}\sqrt{3}$ for the transformer ratios of figure 4. These statements are made on the basis of the equivalent circuit which assumes all impedances are linear and consequently does not include minor effects due to variation of transformer exciting impedance. The line-to-ground performance is a function of both positive- and zero-sequence performances and is expressed mathematically in appendix II.

Where residual voltage only is required, a single device may be used and its zero-sequence performance is the same as its single-phase performance with the three capacitors paralleled at tap and line terminals. The burden rating of such a device refers to the burden on the second-

Figure 4. Equivalent burdens and sequence networks

(*a*)—Polyphase connection of potential devices with burdens on various windings of auxiliary transformers

(*b*)—Shorthand representations

(*c*)—Sequence networks

Table I. Potential-Device Performance Data

Type of Potential Device	Voltage Performance (a)		Burden Performance (b)	
	Ratio Error (Per Cent)	Phase-Angle Error (Deg)	Ratio Error (Per Cent)	Phase-Angle Error (Deg)
Low-capacity bushing device	20	30	35	5
High-capacity bushing device	8	10	20	5
Low-capacity capacitor device	5	5	15	4
High-capacity capacitor device	4	4	10	2
Simplified capacitor device	5	15	35	15

These values indicate: (*a*) The maximum errors to be expected with changes in line voltage of 5 per cent to 120 per cent of rated voltage with the device adjusted for rated watt burden at 66.5 volts, 60 cycles, and rated line-to-ground voltage. (*b*) The maximum errors to be expected with changes in burden of 0 per cent to 100 per cent of rated watt burden when energized at rated line-to-ground voltage, and with the device adjusted, for rated watt burden at 66.5 volts 60 cycles.

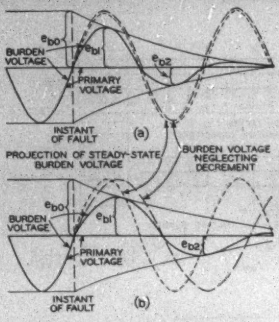


Figure 5. Potential-device transients

(*a*)—Natural frequency equal to system frequency

(*b*)—Natural frequency less than system frequency

ary terminals at rated voltage when zero-sequence voltage is applied at the line terminals. The required ratio from line zero-sequence voltage to burden voltage, in any case, is dependent on system grounding characteristics and is determined in the same manner as the ratio of star-series auxiliary transformers.

Transients—Theory

When a fault occurs there is a lag between the decrease of line voltage to a new level and the time the secondary voltage of the device reaches its corresponding new level, the extent of this lag depending on the network and burden constants. During this time the secondary voltage deviates from its correct value. This difference is in the nature of a damped wave which may be oscillatory or "dead beat" and its importance depends upon the application involved. In the case of a high-speed directional relay, the transient may be of assistance to good relay operation provided the phase shift is small. However, if high-speed impedance relays are used, it becomes desirable to reduce the transient to a value which will not materially extend the relay operating time.

Transient Performance—Series Circuit

The vector diagrams, figure 3, throw considerable light on the transient performance of the potential device. The equivalent circuit, figure 2*d*, derived for steady-state conditions applies also to transient conditions if the transformer magnetizing branch is neglected. The burden which was lumped as a single impedance for the steady-state conditions must be segregated into its actual components for correct analysis of the transient conditions. For example, a pure watt burden consisting of a resistor will have entirely different characteristics under transient conditions, than a lagging-power-factor burden, corrected to unity power factor by a capacitor.

Consider first a pure resistance burden equal to the device rating and the device adjusted for zero-phase angle error. The steady-state proportions, indicated in figure 3*b*, are approximately 1.1, 0.8, and 0.8 for resistance, inductive reactance, and capacitive reactance, respectively. This circuit, therefore, has a natural frequency equal to the normal system frequency. The transient is nonoscillatory or oscillatory depending on whether R^2 is greater than $4X_LX_C$ as shown in appendix III. From the impedance proportions of the vector diagram, it is apparent that the circuit is oscillatory having a logarithmic decrement of 11.5 per cent, that is, the ratio of successive half cycle peaks is 11.5 per cent for the decaying transient voltage. The most severe transient occurs when the high voltage is faulted at the zero point of the voltage wave. In this case, the first crest of burden voltage occurs one-fourth cycle

Figure 6. Single-phase transient tests for high-capacity 230-kv bushing potential device

Primary line-to-ground voltage 127 kv, 60 cycles; secondary voltage 63.5 volts

A—Timing wave
B—Secondary voltage
C—Primary voltage

(*a*)—Secondary burden 10 volt-amperes—100 per cent power factor

(*b*)—Secondary burden 40 volt-amperes—100 per cent power factor

(*c*)—Secondary burden 100 volt-amperes—100 per cent power factor

Figure 7. Single-phase transient tests for high-capacity 138-kv bushing potential device

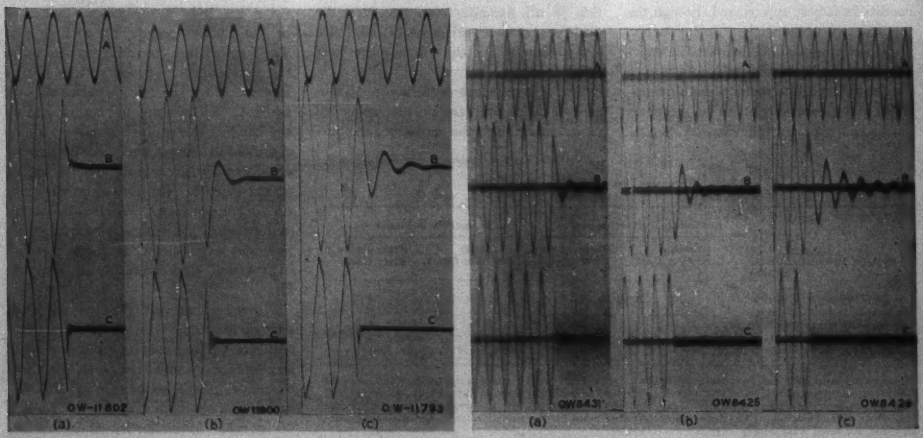
Primary line-to-ground voltage 76.2 kv, 60 cycles; secondary voltage 63.5 volts

A—Timing wave
B—Secondary voltage
C—Primary voltage

(*a*)—Secondary burden 20 volt-amperes—100 per cent power factor

(*b*)—Secondary burden 40 volt-amperes—100 per cent power factor

(*c*)—Secondary burden 40 volt-amperes—50 per cent power factor lagging



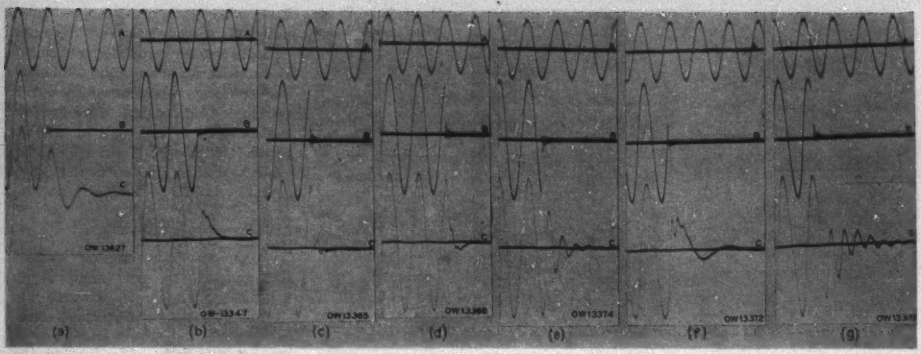


Figure 8. Single-phase transient tests for standard and modified low-capacity 161-kv capacitor potential device

Primary line-to-ground voltage 80.8 kv, 60 cycles; secondary 67.3 volts

A—Timing wave
B—Primary voltage
C—Secondary voltage

(*a*)—Standard device with secondary burden of 65 volt-amperes—100 per cent power factor

(*b*)—Modified device with secondary burden of 65 volt-amperes—100 per cent power factor and fault at voltage zero

(*c*)—Modified device with secondary burden of 65 volt-amperes—100 per cent power factor and fault at voltage peak

(*d*)—Modified device with secondary burden of 100 volt-amperes—100 per cent power factor

(*e*)—Modified device with secondary burden of 60 volt-amperes—50 per cent power factor leading

(*f*)—Modified device with secondary burden of 60 volt-amperes—50 per cent power factor lagging

(*g*)—Modified device with secondary burden of 60 volt-amperes—50 per cent power factor lagging capacitor corrected to unity power factor

after the primary voltage has been faulted, as shown in figure 5. Its magnitude is the normal value of burden voltage multiplied by the square root of the logarithmic decrement or 34 per cent for the proportions of figure 3*b*. Successive peaks are in the ratio of the logarithmic decrement. Thus the transient performance can be predicted directly from the vector diagram. In this particular case, we find that the transient is oscillatory and has successive peak values of 34 per cent, 3.9 per cent, 0.5 per cent, and so forth, provided the high line voltage is short-circuited at the instant it is passing through zero.

At reduced burdens, the current is decreased and, it is apparent that the reactive voltage drops shown in the vector diagram are smaller in direct proportion. For one-fourth burden, the proportions are 1.1, 0.2, and 0.2 for R, X_L, and X_C respectively. The transient is therefore "dead beat" which emphasizes the important point that the transient can be reduced by lowering the burden on the device.

In a similar manner, the natural frequencies and decrements or time constants have been obtained for the other vector diagrams of figure 3, the results being given in table III. From an analysis of this table, it is evident that a device adjusted for zero phase angle (inductive and capacitive reactances of the device equal) does not guarantee a natural frequency equal to the system frequency, since the burden constants also affect the natural frequency. Furthermore, it is evident that this circuit is not necessarily oscillatory, since a reduction of a resistive burden may increase the ratio of R^2 to $4X_LX_C$ to a point where the transient is "dead beat." Also, it is apparent that a decrease in the source capacitive and inductive reactances improves the transient performance for a given burden.

Table II. Correlation of Calculated and Test Transient Data

Figure Number	First Peak in Per Cent of Normal Crest Voltage		Successive Peaks in Per Cent of Previous Peak		Natural Frequency (Calculated)
	Calculated*	Test	Calculated	Test	
6*b*	51.4		26.5	23.2	60.0
6*c*	70.1		49.3	50.0	60.0
7*a*	52.1		27.3	33.3	60.0
7*b*	73.3	74.0	53.9	50.0	60.0
7*c*	81.9		67.2	65.0	53.8
8*a*	63.0		39.7	41.5	60.0
8*f*	63.8		40.9	35.6	37.4

Based on fault at zero point of voltage wave.

Table III. Natural Frequencies and Decrements Corresponding to Figure 3*

Figure Number	First Peak in Per Cent of Normal Crest Voltage		Successive Peaks in Per Cent of Previous Peak		Natural Frequency if Oscillatory		Time Constants in Seconds†	
	100 Per Cent Burden	25 Per Cent Burden	100 Per Cent Burden	25 Per Cent Burden	100 Per Cent Burden	25 Per Cent Burden	100 Per Cent Burden	25 Per Cent Burden
3*a*			45.7	16.4	88.2	117.0	0.00724	0.00193
3*b*	33.8	20.2	11.5	**	60.0	**	0.00386	0.01560
3*c*			49.7	19.2	41.2	26.5	0.00174	0.00115
3*d*			8.4	**	91.0	**	0.00221	0.00807

* Burden composed of resistance and reactance in series. † Long-time constant tabulated for nonoscillatory case. ** Nonoscillatory.

Double-Energy Transients

Two practical cases giving rise to complex circuits are the use of an adjusting capacitor on the transformer secondary

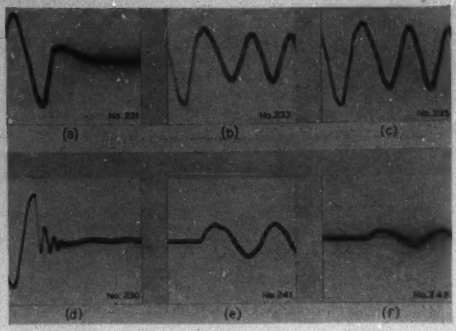


Figure 9. Three-phase transient a-c network calculator tests for modified low-capacity 161-kv capacitor potential device

Primary line-to-ground voltage 80.8 kv, 60 cycles; secondary line-to-ground voltage 67.3 volts. Phase-relay burden 43 volt-amperes—96 per cent power factor lagging; ground-relay burden 29 volt-amperes—75 per cent power factor leading

(*a*)—Phase-relay voltage for fault at device end of line at zero point of voltage wave

(*b*)—Same at middle of line

(*c*)—Same at remote end of line

(*d*)—Same as (*a*) except for fault at peak of voltage wave

(*e*)—Ground-relay voltage for fault at device end of line at zero line point of voltage wave

(*f*)—Same at middle of line

and the use of a capacitor in parallel with the burden for power-factor correction. The first of these in any practical case results in a high-frequency transient of short duration which is unimportant. The latter may produce an undesirable double-frequency transient. In the particular case of correction to unity power factor, the two frequencies are respectively above and below normal system frequency and correspond to the resonance points between the series-connected source impedances and the parallel-connected burden impedances.

Resonance

The terms "resonant", "oscillatory", "nonresonant", and so forth, have been somewhat loosely used in connection with potential devices in the past. In view of the foregoing discussion, they should be analyzed in an effort to define their meaning as applied to these devices and, if possible, to adopt more appropriate nomenclature for the various devices available.

The term "nonresonant" applies strictly to steady-state conditions. It is, however, ambiguous and has in some cases been confused as implying a freedom from the effects of oscillation of the burden voltage when changing to a new level. Nonresonant devices are actually a simpler, cheaper form of device, termed "nonresonant" because they do not have the equal capacitive and inductive reactive branches in the source. Actually, this simply means that such a device does not resonate at system frequency with a pure resistance burden. It will, of course, resonate at some other frequency if the burden includes inductance, as it usually does, and will involve the double-energy transients mentioned above if corrective capacity is used with the burden. The term "nonresonant" has also been used to distinguish such a device from the resonant device which has good regulation. Since the standard potential devices (so called "resonant" devices) may have superior performance characteristics under both steady-state and transient conditions, it would be preferable to distinguish them from the less elaborate arrangement by referring to the latter as the "simplified" device, which would not involve any implication as to its relative transient performance.

Transient Test Data

A comprehensive series of transient tests were made to verify the theory outlined above, as well as to show the transient characteristics which may affect the performance of high speed relays, and the efficacy of several means of control. These investigations included field tests previously described,[2,3] single-phase fault tests made on typical devices in the factory, and a-c network-calculator tests.

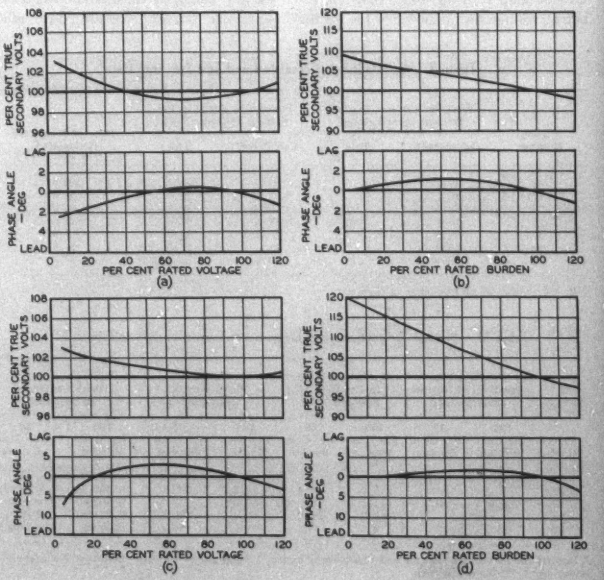
Figure 10. Capacitor and bushing potential-device performance curves

(*a*)—High-capacity 161-kv 60-cycle capacitor potential device—voltage performance

(*b*)—High-capacity 161-kv 60-cycle capacitor potential device—burden performance

(*c*)—High-capacity 161-kv 60-cycle bushing potential device—voltage performance

(*d*)—High-capacity 161-kv 60-cycle bushing potential device—burden performance



In the latter the recently devised method[4] for utilizing the a-c network calculator for transient studies was employed. While 115 and 66.5 volts are the standard line-to-line and line-to-neutral voltages,

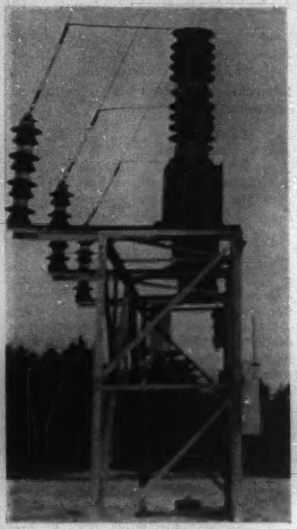


Figure 11. Low-capacity 115-kv capacitor potential device equipped for carrier-current coupling

respectively, the test data have been taken at the various service voltages indicated in the captions.

Figures 6, 7, and 8 illustrate typical single-phase tests, and in general show natural frequencies, amplitudes, and decrements of the burden voltage transient as expected from the theoretical analysis, this correlation being indicated in table II. Since the point of voltage wave at which fault occurs was not controlled in these tests, the magnitude of the first peak after the fault could be compared only in the one case where the fault occurred at the zero point of the voltage wave. Of particular interest are the effects of burden variations figures 7*b* and *c*, and figures 8*c*, *e*, *f*, and *g*. Figures 8*a* and *b* illustrate the improvement obtained by modifying the device as suggested by the theory. Figure 8*g* shows the double-energy transient resulting from power-factor correction of the burden by parallel capacitor. The "subtransient" resulting from the use of adjusting capacitors on the secondary of the transformer is evident in several of the oscillograms of figure 8. Comparison of figures 8*b* and *c* illustrates that the maximum overshoot is obtained for a fault at the zero point of the voltage wave.

The a-c network calculator has been shown to give natural frequencies, amplitudes, and decrements of the transient in close agreement with theoretical methods and with results obtained by oscillographic tests on actual devices. Its flexibility has made possible a thorough analysis covering a wide range of conditions. This study has included for example the effect of location of fault along the transmission line, the effect of point on the voltage wave at which a fault occurs, and of different types of faults such as three phase, line-to-line, line-to-ground, and double line-to-ground. The effects of various proportions and arrangements of the device parts have been studied, a modified device having resulted from this study. The transients have been observed on the ground relays and on the phase relays of sound and faulted phases with balanced and unbalanced arrangements of relay burdens.

Typical photographic records of these tests are given in figure 9, parts *a*, *b*, and *c* illustrate the effect of moving the fault along the transmission line, *a* and *d* the effect of point on the voltage wave at which the fault occurs, and *e* and *f* show the ground relay voltage for faults at the zero and peak points of the voltage wave. The subtransient is maximum for faults at the peak of the wave where a quick energy dissipation in the capacitance divider is necessary. The main transient is greatest for fault at the zero point of the wave.

Conclusions

A general method has been presented utilizing an equivalent circuit for analyzing the performance of potential devices from a design and application standpoint, a method which offers an advantageous point of view for visualizing the phenomena involved as well as providing the specific solutions. This method, including the use of symmetrical components for unbalanced system conditions, covers both steady-state and transient performance. The a-c network-calculator method of transient testing has been found to give reliable engineering results in this problem even though both the power system and measuring system constants needed to be represented simultaneously on the calculator circuits.

Improvements in transient performance have been found possible by changes in design constants, and tests on devices built in line with the theory have shown the expected improvements. It has been shown that the transient phenomena is roughly divisible into a subtransient due to adjusting capacity on the secondary of the transformer, and a main transient in the series circuit composed of the device and its burden. The subtransient is negligible due to its short duration and high frequency. The main transient is of considerable importance, and proper control should be exercised in design and loading to keep it within application requirements. Low noninductive burdens result in the best performance. Double-energy main transients may be avoided by omission of burden-paralleling capacitors.

The studies described have afforded basis for the design of a new capacitor potential device utilizing a variable reactance transformer and having windings for supplying simultaneously star- and delta-connected phase burdens and residual burdens.

Appendix I. Steady-State Performance

Nomenclature

FUNDAMENTAL CONSTANTS

On circuit voltage base, refer to figure 2 except as noted.

Z_a —Impedance of stack capacity
Z_c —Impedance of tap capacity
Z_x —Transformer exciting impedance, primary basis
Z_l —Transformer leakage impedance, primary basis
n —Transformer turns ratio, high voltage to low voltage
Z_s —Impedance of tuning capacity, in parallel with tap capacity but located on secondary side of transformer
Z_r —Impedance of the variable reactor
Z_b —Burden impedance
Z —Source impedance to burden, secondary basis
E_h —High line voltage to ground
E_a —Tap voltage to ground
E_b —Burden voltage
E_{bo} —Burden no-load voltage
A —Over-all potentiometer effect multiplier
k —Over-all no-load transformation ratio E_h/E_{bo}

$$\frac{1}{k}=\frac{A}{n}$$

Other derived and intermediate quantities are defined by the equations.

DERIVATION OF EQUIVALENT CIRCUIT, FIGURE 2 (dotted capacitor not used)

In figure 2*b* the parallel of Z_c and Z_x is

$$Z_{cx}=\frac{Z_cZ_x}{Z_c+Z_x} \qquad (1)$$

By Thevenin's theorem the potentiometer circuit composed of Z_a and Z_{cc} may be replaced by the simple series circuits of figure 2c in which:

$$nE_{bo}=\frac{Z_{cc}}{Z_a+Z_{cc}}E_b=AE_b \tag{2}$$

where E_{bo} is seen to be the burden no-load voltage.

$$A=\frac{Z_{cc}}{Z_a+Z_{cc}} \tag{2a}$$

$$Z_{acc}=\frac{Z_{cc}}{Z_a+Z_{cc}}Z_a \tag{3}$$

and being essentially capacitive reactance is shown as such. The transformer leakage impedance and the reactor combine to form the inductive reactance of the source,

$$n^2Z_{tr}=Z_t+n^2Z_r \tag{4}$$

In figure 2d the secondary turns base has been used although this is purely a matter of preference. The total source impedance on this base is:

$$Z=\frac{Z_{acc}}{n^2}+Z_{tr} \tag{5}$$

The "burden performance" of the device, or ratio and phase-angle regulation, may be expressed in the form:

$$E_b=E_{bo}-I_bZ \tag{6}$$

$$E_b=\frac{A}{n}E_h-I_bZ \tag{6a}$$

where the no-load voltage E_{bo} and the source impedance Z are defined above.

Derivation of Equivalent Circuit, Figure 2 (dotted capacitor used)

The capacitance divider and transformer exciting impedance can be converted as before to an equivalent series circuit having internal voltage E_a and impedance Z_{acc} defined as follows.

$$Z_{cc}=\frac{Z_eZ_s}{Z_e+Z_s} \tag{7}$$

$$E_a=\frac{Z_{cc}}{Z_a+Z_{cc}}E_h \tag{8}$$

$$Z_{acc}=\frac{Z_{cc}}{Z_a+Z_{cc}}Z_a \tag{9}$$

Combining the source with the transformer leakage impedance, the new source impedance Z_{accr} is defined, the internal voltage being still given by (8)

$$Z_{accr}=Z_{acc}+Z_t \tag{10}$$

On the primary turns base the adjusting capacitor has an impedance n^2Z_r. Converting the potentiometer circuit formed by Z_{accr} and n^2Z_r by a series circuit, according to Thevenin's theorem, an internal voltage nE_{bo} and impedance Z_{accrn} are obtained.

$$nE_{bo}=\frac{n^2Z_r}{n^2Z_r+Z_{accr}}E_a=\frac{n^2Z_r}{n^2Z_r+Z_{accr}}\cdot\frac{Z_{cc}}{Z_a+Z_{cc}}E_a \tag{11}$$

or

$$nE_{bo}=AE_h \tag{12}$$

where

$$A=\frac{n^2Z_r}{n^2Z_r+Z_{accr}}\cdot\frac{Z_{cc}}{Z_a+Z_{cc}} \tag{13}$$

Also

$$Z_{accrn}=\frac{n^2Z_r}{n^2Z_r+Z_{accr}}Z_{accr} \tag{14}$$

This term is essentially capacitive in cases where the adjusting capacity is used at all, and corresponds roughly to z_{acc} of figure 2d. Combining it in series with the reactor, the over-all source impedance Z becomes on the secondary turns base:

$$Z=\frac{Z_{accrn}}{n^2}+Z_r \tag{15}$$

and the burden performance characteristic is:

$$E_b=E_{bo}-I_bZ \tag{16}$$

or

$$E_b=\frac{A}{n}E_h-I_bZ \tag{16a}$$

where A and Z are defined by equations 13 and 15.

Appendix II. Symmetrical-Component Resolution

(Refer Also to Appendix I)

Nomenclature

E	—Voltage
a, b, c	—Phases
$1, 2, 0$	—Sequences
h	—High-voltage line
p, u, v, w	—Turns or turns base designation

Examples: E_{a2}, negative-sequence voltage, line-to-neutral at location indicated in figure 4 on turns base u; E_{b1}, positive-sequence component of the set E_{ha}, E_{hb}, E_{hc}.

In figure 4 the derivation of sequence networks on the particular turns base u follows well-known theory. The ratio n used in determining Z and the applied voltage should include not only the main transformer, but also the auxiliary transformer from p to u. The auxiliary transformer when liberally designed may be treated as a "perfect" transformer of negligible exciting and leakage impedances or if not negligible it may be treated as a three-winding transformer since not more than three windings are involved in any sequence network. The zero-sequence impedance on turns base u due to the load Z_{bw} is in general $\frac{Z_{bw}}{3}\left(\frac{u}{w}\right)^2$ which for the particular ratio shown is $Z_{bw}/9$.

The corresponding general expression for E_{bw} is

$$E_{bw}=3\frac{w}{u}E_{w0} \tag{17}$$

Under both normal and fault conditions the voltage E_{ha}, E_{hb}, E_{hc}, and hence the voltages E_{h1}, E_{h2}, E_{h0}, will be fixed rigidly by the power-system constants and the type and location of fault.

The corresponding burden sequence voltages are determined from the sequence networks, figure 4c.

$$E_{u1}=\frac{Z_{b1}}{Z+Z_{b1}}\frac{A}{n}E_{h1} \tag{18}$$

$$E_{u2}=\frac{Z_{b2}}{Z+Z_{b2}}\frac{A}{n}E_{h2}=\frac{Z_{b1}}{Z+Z_{b1}}\frac{A}{n}E_{h2} \tag{19}$$

$$E_{u0}=\frac{Z_{b0}}{Z+Z_{b0}}\frac{A}{n}E_{h0} \tag{20}$$

From these the burden line-to-neutral voltages are obtained

$$E_{ua}=\frac{A}{n}\left[(E_{h1}+E_{h2})\frac{Z_{b1}}{Z+Z_{b1}}+E_{h0}\frac{Z_{b0}}{Z+Z_{b0}}\right] \tag{21}$$

$$E_{ub}=\frac{A}{n}\left[(a^2E_{h1}+aE_{h2})\frac{Z_{b1}}{Z+Z_{b1}}+E_{h0}\frac{Z_{b0}}{Z+Z_{b0}}\right] \tag{22}$$

$$E_{uc}=\frac{A}{n}\left[(aE_{h1}+a^2E_{h2})\frac{Z_{b1}}{Z+Z_{b1}}+E_{h0}\frac{Z_{b0}}{Z+Z_{b0}}\right] \tag{23}$$

Adding and subtracting a zero-sequence term:

$$E_{ua}=\frac{A}{n}(E_{h1}+E_{h2}+E_{h0})\frac{Z_{b1}}{Z+Z_{b1}}-E_{h0}\frac{Z_{b1}}{Z+Z_{b1}}+E_{h0}\frac{Z_{b0}}{Z+Z_{b0}}$$

$$=\frac{A}{n}\frac{Z_{b1}}{Z+Z_{b1}}E_{ha}+E_{h0}\frac{A}{n}\left[\frac{Z_{b0}}{Z+Z_{b0}}-\frac{Z_{b1}}{Z+Z_{b1}}\right] \tag{24}$$

Similarly

$$E_{ub}=\frac{A}{n}\frac{Z_{b1}}{Z+Z_{b1}}E_{hb}+E_{h0}\frac{A}{n}\left[\frac{Z_{b0}}{Z+Z_{b0}}-\frac{Z_{b1}}{Z+Z_{b1}}\right] \tag{25}$$

$$E_{uc}=\frac{A}{n}\frac{Z_{b1}}{Z+Z_{b1}}E_{hc}+E_{h0}\frac{A}{n}\left[\frac{Z_{b0}}{Z+Z_{b0}}-\frac{Z_{b1}}{Z+Z_{b1}}\right] \tag{26}$$

Equations 24, 25, and 26 show that with zero-sequence voltage present, and zero- and positive-sequence burdens unequal, the ratio of high to burden line-to-neutral voltages is not a constant, but depends on the zero-sequence voltage, the difference in burdens (Z_{b0} and Z_{b1}) and the stiffness of the device (value of Z). If Z is small, both terms in the parenthesis approach one resulting in a relatively small voltage error. Also if the positive- and zero-sequence burdens are made equal the voltage error can be eliminated.

The delta voltages may be obtained by subtracting equations 24, 25, and 26 in pairs and defining the high line-to-line voltage as

$$E_{hab}=E_{ha}-E_{hb} \tag{27}$$

$$E_{uab}=E_{ua}-E_{ub}=\frac{A}{n}\frac{Z_{b1}}{Z+Z_{b1}}E_{hab} \tag{28}$$

$$E_{ubc}=\frac{A}{n}\frac{Z_{b1}}{Z+Z_{b1}}E_{hbc} \tag{29}$$

$$E_{bzo} = \frac{A}{n} \frac{Z_{b1}}{Z + Z_{b1}} E_{bco} \tag{30}$$

Equations 28 to 30 show that the ratio of high to burden delta voltages is a constant independent of the residual burden, the system constants, and type of fault.

The residual voltage is

$$E_{bw} = 3\frac{w}{u} E_{wo} \tag{31}$$

and from equation 20

$$E_{bw} = 3\frac{w}{u} \frac{Z_{b0}}{Z + Z_{b0}} \frac{A}{n} E_{b0} \tag{32}$$

Equation 32 shows that the ratio of high zero-sequence voltage to residual voltage is a constant independent of the amount of delta burden, the system constants, and the type of fault.

Appendix III. Transients

The equivalent circuit, figure 2*d*, with the slight approximation of ignoring Z_z, is also an equivalent under transient conditions. It shows that the device and its connected burden may be treated as a series circuit of R, L, and C, provided the burden approximates a resistance or resistance and reactance in series. Tests indicate that this is generally the case unless burden-power-factor-correction capacitors are used.

It is well known that the R, L, C series circuit is oscillatory only if

$$R^2 \text{ is less than } \frac{4L}{C}$$

or if

$$R^2 \text{ is less than } 4X_L X_C$$

where X_L and X_C are the inductive and capacitive reactances at any arbitrary frequency such as 60 cycles. If R^2 is greater than given by this value, the circuit is not oscillatory but "dead beat."

Nonoscillatory Case

R^2 is greater than $4L/C$.

The solution for current i, as a function of time t, for pure resistance burden with fault occurring at the instant of current zero (which coincides with burden voltage zero) is a unidirectional surge as follows.

Burden Current

$$i = A(\epsilon^{\frac{-t}{T_1}} - \epsilon^{\frac{-t}{T_2}}) \tag{33}$$

where

$$A = \frac{\sqrt{2}E_0}{L} \frac{T_1 T_2}{T_1 - T_2} \tag{34}$$

in which E_0 is the root-mean-square capacitor voltage prior to the fault.

Time Constants

$$T_1 = \frac{2L}{R - \sqrt{R^2 - \frac{4L}{C}}} \text{ seconds} \tag{35}$$

$$T_2 = \frac{2L}{R + \sqrt{R^2 - \frac{4L}{C}}} \text{ seconds} \tag{36}$$

T_1 is the long-time constant determined largely by RC, and fixes the decay of the surge. T_2 is the short-time constant determined largely by L/R and determines the shape of the front of the wave. The exact values are given by equations 35 and 36.

The burden voltage following the fault is:

Burden Voltage

$$e_b = iR_b = R_b A(\epsilon^{\frac{-t}{T_1}} - \epsilon^{\frac{-t}{T_2}}) \tag{37}$$

This is a unidirectional surge of voltage which reaches its crest in a time:

Time to Crest

$$t_m = \frac{T_1 T_2}{T_1 - T_2} \log \frac{T_1}{T_2} \tag{38}$$

Crest Value

$$e_b \max = R_b A(\epsilon^{\frac{-t_m}{T_1}} - \epsilon^{\frac{-t_m}{T_2}}) \tag{39}$$

Oscillatory Case

R^2 less than $4L/C$.

The solution for fault occurring at the zero point of the voltage wave with pure resistance burden is an oscillation of the form

$$e_b = e_{b0}\epsilon^{\frac{-t}{T}} \sin 2\pi f_0 t \tag{40}$$

where e_{b0} is the crest value of steady-state voltage prior to the fault.

The characteristic factors are given as follows:

Natural Frequency

$$f_0 = \frac{1}{4\pi L}\sqrt{\frac{4L}{C} - R^2} \text{ cycles per second} \tag{41}$$

Time Constant

$$T = \frac{2L}{R} \text{ seconds} \tag{42}$$

Ratio of Successive Peaks or Decrement (Refer to figure 5)

$$D = \frac{e_{b2}}{e_{b1}} = \epsilon^{\frac{-1}{2Tf_0}} = \epsilon^{\frac{-R}{4Lf_0}} = \epsilon^{\frac{-\pi R}{2X_{L0}}} \tag{43}$$

where the inductive reactance at natural frequency is X_{L0}.

Successive peaks are one-half cycle apart whereas the initial peak occurs but one-fourth cycle after the fault. The first peak is:

First Peak

$$\frac{e_{b1}}{e_{b0}} = \sqrt{D} \tag{44}$$

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Discussion

H. A. P. Langstaff (West Penn Power Company, Pittsburgh, Pa.): The West Penn Power Company has made extensive use on the 132-kv transmission system of the bushing-type potential device closely allied in characteristic operation with the pedestal or suspension-type capacitor potential device, none of which have been used. Thirty-six bushing potential devices are now in active service located at seven 132-kv substations. The evident economy in cost of apparatus and in simplification of structure layout has well warranted the selection and use of this equipment. Purchase and installation has extended from 1927 to the present year; the two original devices purchased in 1927, rebuilt and modernized, are still in service.

The uses to which the devices have been put are as follows:

1. To obtain potential indication and source of synchronizing potential for incoming 132-kv lines. In two instances synchronism is checked from a device on one line to a device on another line. In other instances it is from a line device to a standard potential transformer. Where a phase difference occurs such as in synchronizing from the phase-to-ground-connected device to a phase-to-phase-connected potential transformer it has been compensated for by adjusting the phase angle of the potential device, a very convenient and wholly satisfactory method.

2. To obtain potential for directional phase relays and with the use of an auxiliary star-series potential transformer for directional ground relays.

3. To obtain zero-sequence potential for directional ground relays. In this instance a three-phase potential unit was constructed composed of two open-delta-connected standard 132-kv potential transformers, to the three external 132-kv bushings of which were attached three bushing potential devices. The potential transformers are used for directional phase relays and the bushing potential devices supply zero-sequence voltage for directional ground relays. Two of these complete three-phase units are installed at Charleroi substation, one on each section of the 132-kv bus. To each unit is connected the phase and ground protective relays of four incoming 132-kv lines. These units, designed by West Penn Power Company and assembled by the Westinghouse Electric and Manufacturing Company constituted an economical and satisfactory means of obtaining the desired result using potential transformer cores available for that purpose. The tanks are large enough to take a third potential transformer core.

4. At the Kiski Valley substation three devices on a 132-kv breaker are connected to detect zero-sequence potential and to cause the breaker to trip, if a 132-kv ground fault persists for a period exceeding the time setting of a voltage relay. (The 132-kv bank winding is delta connected at this substation.)

The first potential device was put in service on May 10, 1928, and was used for 132-kv line potential indication and for synchronizing. An article by the writer in the *Electrical World* of November 24, 1928, described this application. On April 6, 1938, a series of 132-kv ground-fault tests was made on a complete directional phase and ground relay application at Washington substation where two incoming 132-kv lines connected to a bus from which power was distributed through two 15,000-kva banks. One bushing on the line side of each

line breaker was equipped with a potential device for line potential indication and for synchronizing. Three devices on the bus side bushings of each breaker supply potential to phase and ground protective relays. Oscillograph records were taken by the Westinghouse company and the analysis proved the acceptability of the potential devices for protective work.

Troubles and poor performance which were experienced on the devices purchased during their early stage of development were due almost wholly to causes originating in the lead-in cables. Corona deterioration occurred in the cables and breakdown occurred in the bayonet due to moisture entering through poorly made joints. About 20 cables were replaced in 1931 and some of them have given trouble since that time from the same causes. Due to this experience bayonet and cable improvements have been made and the present connected bayonet and cable gives promise of being free from the past troubles.

A special star-series auxiliary potential was designed for West Penn Power Company use in order that zero-sequence potential might be obtained and it has been used with complete success with the potential devices. In figure 4*a* of the paper under discussion is shown an auxiliary transformer, apparently now an integral part of the potential device, which makes available without any external apparatus voltage for line-to-neutral burden, line-to-ground burden, and residual burden. The Westinghouse company is to be congratulated upon this improvement.

The performance on the West Penn Power Company 132-kv system of the potential devices has been entirely satisfactory so far as electrical characteristics are concerned. They have not been called upon to operate with relays of the impedance type or of modern high-speed nature. Hence many of the problems and their solution discussed in this paper by Messrs. Harder, Langguth, and Woods have not been encountered, sufficient time of relay operation having obviated the effect of transient variations.

J. D. Laughlin and **T. M. Blakeslee** (Bureau of Power and Light, City of Los Angeles, Calif.): From an operating standpoint, it is gratifying to read a paper demonstrating such complete concordance of performance with theory as is disclosed in the paper by Messrs. Harder, Langguth, and Woods.

The protection of important transmission lines with high-speed relays has developed to a point where it is highly desirable, if not absolutely necessary, that potential sources, as well as current sources, for the relays be obtained from devices inside the protected circuit.

Instrument potential with sufficient accuracy for relaying purposes can be obtained from capacitor potential devices and the capacitors can also be used as coupling devices for carrier-frequency circuits. The dual functions of these devices and their lower cost justifies their use in many installations that might be questioned if standard potential transformers had to be used.

Since the most important use of these devices is for obtaining relay potential, and as relays function only under fault conditions on a system, it seems highly important that these devices be designed to reproduce accurately the primary voltage conditions when the system voltage is low and to remain stable when surges appear on the line.

As explained in the paper, there are many variations of the device circuit, some of which are not adaptable to all applications. The oscillograms in the paper show that for some secondary circuits with resonant characteristics the secondary voltage may continue for a time after the interruption of the primary voltage. This condition is undesirable for applications using relays with potential restraint coils that are expected to function in less than one cycle. The accurate predetermination of performance is necessary to select the proper type of device for specific applications.

The development of potential devices with multiple secondary voltages for obtaining delta, star, and residual voltages has simplified relay installations.

Prior to the application of potential devices on the Boulder transmission lines, instability, due to the parallel circuit made up by the auxiliary or tap capacity and the device transformer, was discovered in certain capacitor potential devices by our testing laboratories. This was corrected, however, before extensive use of the units, with the result that their performance in service has been satisfactory. This unstable phenomenon is that referred to by Mr. Clem (reference 6) and was corrected by designing the device transformer with low magnetic density so that the circuits approach the linearity assumed in the mathematical analysis presented in the paper under discussion.

The Los Angeles Bureau of Power and Light has accepted the increasing popularity of capacitor potential devices. All 287,500-volt lines are completely equipped to provide potential for relays, meters, indicating lamps, and for synchronizing. The capacitors are also used to couple carrier-frequency circuits to the lines, there being three carrier-frequency circuits operating over each transmission circuit. The bulk of the 110-kv and 132-kv lines are also fully equipped, and there are some installations on 34.5-kv lines.

Since the potential device bids fair to take the place of the more expensive potential transformer in every application, except that of power metering, some standardization of nomenclature would be desirable. The present paper points out the ambiguity of the terms "resonant" and "nonresonant." The capacity, which is in series with the line, is identified by the authors of this paper as the "stack capacity," whereas other authors refer to this as the "coupling capacity." The capacitor in parallel with the potential device is called the "tap" and "auxiliary" capacity, respectively, by different authorities.

The ability of the manufacturer to predict accurately the performance of these devices, as disclosed in this paper, will be of great assistance to application engineers by permitting them to take full advantage of their uses, select the proper type of devices for individual applications, and use them with confidence.

L. F. Kennedy (General Electric Company, Schenectady, N. Y.): Successful relay application requires complete knowledge of the characteristics of the sources of supplies of current and potential. This paper dealing, as it does, with a frequently used source of potential is of interest to all relay engineers. The fact that it recognizes the importance of the transient as well as the steady-state conditions of potential devices should make it of increased value.

The requirements for a supply of relay potential may be very briefly summarized as follows: For directional relays the phase-angle error should be small and reasonably constant; for distance relays or other relays using voltage restraint the ratio error should be small. Both types of relays of modern construction are precision instruments carefully designed to operate correctly under certain assumed conditions.

Let us consider for a moment what has been shown in the paper by Mr. Harder and his associates. Figure 8*a* shows that several half cycles of apparently normal frequency are required for one standard potential device secondary voltage to reach zero after the primary voltage has been made zero. Other illustrations show various transients of which some are negligible and others persist for several oscillations. These latter show frequencies which vary from half normal to more than twice normal.

The first type of transient, that in which there is no change in frequency, but only a time delay before reaching a new level, will in general have only the effect of slowing up the relay response. The second type, that in which there is a change in frequency, must be separately considered for different types of relay elements. As already indicated, the relays are designed for precision operation under certain assumed conditions, one of which is that energy is supplied at rated frequency. It is, of course, obvious to all of us that a modern high-speed directional relay energized with current at normal frequency but with a voltage of half normal frequency as shown in figure 8*f* would respond erratically and oscillate each half cycle instead of producing its expected steady torque in one direction.

Other types of relays will, of course, respond differently and each kind must be separately investigated. Some relays have circuits which are carefully tuned for normal frequency and these cannot help but be affected by changes in frequency.

The ideal potential supply, therefore, would seem to have as its first requirement a low and fixed phase-angle error under transient as well as steady-state conditions; thus any frequency shift is prevented. As a second requirement, of course, would be a low and fixed ratio error but if there was a transient error which resulted in a secondary voltage which at times was higher than expected (as in figure 8*a*), this could be used except in rare cases where the slight increase in over-all time of relay operation was of the utmost importance.

The authors have concluded that a low burden which is noninductive will give the best results and that burden-paralleling capacitors should be avoided. All relay potential coil circuits are inductive and to obtain the noninductive load, it is necessary either to especially design the relay elements with series capacitors to obtain the noninductive circuit for potential device applications only, or if a standard relay applicable to other sources besides the po-

tential device is used, then the noninductive characteristics of the load can only be obtained by the use of paralleling capacitors. We should not overlook the fact, at this part of the discussion, that many relays, which have what appears a noninductive burden, obtain this through the use of internally mounted capacitors. This paper, while pointing out in its theoretical considerations how to obtain the desired results, fails to complete the job by insertion of tabular data which the average application man could use to determine whether or not his particular case would have trouble from transients.

I was rather surprised to note in appendix III that the equivalent circuit under transient conditions was set up by making the approximation of omitting Z_x. Since Z_x represents the magnetizing or exciting component, it is somewhat surprising to find this element ignored in any transient study. It may be that the potential device is greatly different from all other circuits containing an iron-core element, but past experience certainly indicates that the variations in the value of Z_x under various transient conditions would play a very large part in determining the over-all device performance. I will be glad to have the authors' comments on what recorded data they have which justifies this assumption.

Ralph Higgins (The Ohio Brass Company, Barberton, Ohio): Secondary transients have long been recognized as one of the inherent characteristics of capacitance potential devices and the authors additional contribution to this problem is indeed a worthy effort and quite instructive. To reduce the transient effect, the authors of this paper have shown that the best results can be expected when the burden requirements, both the resistive and the inductive components, are reduced to a minimum. While this is quite true, an impression is apt to be conveyed that one must limit the burden requirements when desiring to operate high-speed relays from capacitance potential devices. Thus, it would seem that the economies effected by the use of this potential device would be questionable if one must limit the available output from this type of equipment which already has a limited output. Also, it is noted that the authors have stressed the effect of the burden-paralleling capacitance generally used to adjust the phase-angle relation and to correct the power factor of the burden.

Figure 1 of this discussion shows a simple modification of the usual capacitance-potential-device circuit which may be employed very effectively to dampen out any undesired transient oscillations, and at the same time, this scheme requires only a slight reduction in the available output. Quite a few successful installations have been made of this scheme within the last few years.

This damping effect is accomplished by means of two adjusting resistors, one in parallel with the burden, the other in parallel with the transformer secondary. The usual adjusting capacitor, instead of being connected directly in parallel with the burden, as is the usual practice, is connected from one side of the burden to a higher tap on the transformer secondary. Hence any oscillatory circuit that may be set up in series with this capacitance will also be in series with the transformer winding; and thereby can be made nonoscillatory or deadbeat by means of the resistor paralleling this winding.

Figure 2 shows a few typical oscillograms taken during a three-phase laboratory setup, using 138-kv bushing potential devices energized to full potential, to simulate double line-to-ground faults close to the station. This type of fault, perhaps, presents the most hazardous condition resulting from transients upon the operation of high-speed directional line relays.

Oscillogram *A*, taken of the voltage across the relay on the short-circuited secondary phase, illustrates the effectiveness of the damping accomplished with the potential devices loaded to the full rated output, and with a highly inductive burden. While the transient as shown by this oscillogram is not completely damped within the first cycle, and therefore the transient performance may not be ideal, nevertheless, repeated tests show that successful relay operation could be expected from the arrangement.

Oscillogram *B* illustrates the improvement accomplished by reducing only the inductive component of the burden, and oscillogram *C* that accomplished by a further reduction of both the resistive and inductive components.

We are in full agreement with the authors' objection to the classification of various types of potential devices as either resonant or nonresonant. The term "resonant" is usually associated with a circuit requiring accurate tuning. To obtain the desired adjustment with the network, as shown in figure 1, the potential device can be given an in-phase adjustment, and yet no part of the network need be in resonance at the normal operating line frequency. Also, with the same set of adjusting impedances required for an in-phase adjustment, it is possible to obtain practically any other desired phase-angle relation from 30 degrees lagging to 120 degrees leading with very little change in the available output. Figure 3 is a schematic diagram of such an arrangement. The adjustments requiring a large lead angle are accomplished by simply connecting the adjusting reactor in parallel with the burden. Since the one type of potential device may be made applicable to all normal requirements, it naturally may not come under the nomenclature of resonant or nonresonant.

Another important advantage gained by the use of this network scheme is that numerous tap connections on the transformer are not necessary to meet the normal adjustment requirements of the potential

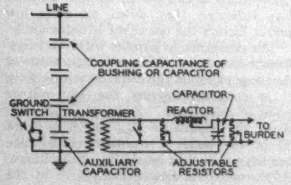

Figure 1

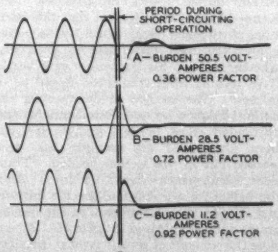
PERIOD DURING SHORT-CIRCUITING OPERATION
A— BURDEN 50.5 VOLT-AMPERES 0.36 POWER FACTOR
B— BURDEN 28.5 VOLT-AMPERES 0.72 POWER FACTOR
C— BURDEN 11.2 VOLT-AMPERES 0.92 POWER FACTOR

Figure 2

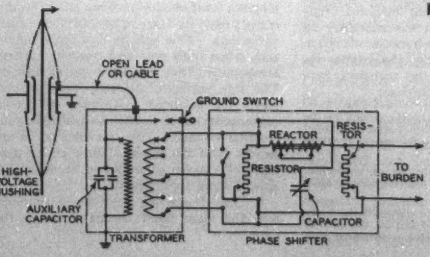

Figure 3

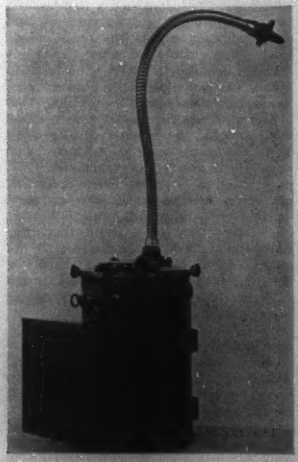

Figure 4

device. This feature readily permits the mounting of the various adjusting impedances in a small cabinet separate from the transformer housing. Figure 4 shows the improved standard potential device used in connection with capacitance tap bushings. Since only three leads are used between the transformer and the adjusting network, it is sometimes found convenient to mount this cabinet in the station close to the burden.

C. A. Powel (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The potential devices referred to in this paper are those used in connection with transformer or circuit-breaker bushings or with coupling capacitors to obtain potential from high-voltage circuits without the use of the more usual but more expensive potential transformer. The Westinghouse company first devised these capacitance transformers back in 1928 by the simple process of tapping the outside layers of their well-known condenser bushings. The low-voltage tapped section of the capacitor supplies a network device consisting of a small transformer, adjustable reactors and capacitors variously connected, depending on what it is to be used for.

With the advent of high-speed relaying, it was found that the potential devices built for other purposes did not give entirely satisfactory results with such relays, which operate in from one to three cycles. When the line potential fell, the secondary voltage in these devices was found not to follow immediately, and, moreover, it might oscillate about the new level for several cycles. If it happened that the line potential went to zero, the secondary voltage might even overshoot so that the relay obtained an indication of voltage in the wrong direction.

In the course of solving this difficulty, the authors developed an analytical method of investigating what happens in the devices under transient as well as steady-state conditions. To date, such a tool has not been available. The analytical method can readily be carried out for a simple single-phase circuit, but when the circuit becomes involved by virtue of unbalanced faults, the analytical work becomes very burdensome if not almost impossible.

The authors, therefore, for such cases, have adopted the method developed by R. D. Evans and A. C. Monteith described in AIEE TRANSACTIONS, volume 56, 1937, pages 695–703, of setting up the equivalent circuits on the network calculator and have actually applied the faults in which they are interested. They have found that they thus obtain reliable results and their studies afforded a basis for the design of a capacitor potential device capable of giving a correct voltage ratio for short time operations as fast as one cycle.

The steady-state analysis may also be complicated when delta, residual, and star-connected burdens are on the same device. The delta burden involves the positive- and negative-sequence circuits, the residual burden involves the zero-sequence circuit, and the star burden involves all three. Through the concepts of symmetrical components, the performance of the device with respect to each burden can be determined and the criteria set up to obtain a design giving uniform results for all burdens. The paper describes in detail how this is accomplished.

E. L. Harder, P. O. Langguth, and C. A. Woods: The several discussers have added valuable comments and supplementary information indicative of the rather widespread interest in the transient performance of potential devices.

1. Mr. Langstaff brings out a very important point which deserves emphasis, namely that with normal-speed relays the transient performance is relatively unimportant because the relay operating time extends beyond the transient period.

2. Messrs. Laughlin and Blakeslee have indicated that installations of capacitor potential devices are being made very generally on their important line projects and it may be noted that this is generally true of all major transmission projects of recent date. These discussers have further emphasized the desirability for standardization of nomenclature. The functioning of the over-all device may best be viewed as a double transformation, the first consisting of a capacitance potentiometer and the second consisting of the transformer. The entire potentiometer comprising two sections which we have called the "stack capacity" and the "tap capacity" constitute the coupling to the power circuit. Hence, these terms seem more significant than the words "coupling capacity" and "auxiliary capacity."

3. That the complete analysis of the transient performance involves consideration of the specific relay performance as well as that of the device is well brought out in the discussion by Mr. Kennedy. He points out that the obtaining of frequencies other than normal would be objectionable for relays carefully tuned to normal frequency. It is our feeling that relays dependent upon system frequency being accurately maintained are to be avoided in any case in view of departure of system frequencies from normal during system disturbances. Mr. Kennedy also has suggested that the insertion of tabular data, which the average application man could use to determine whether or not his particular case would have trouble from transients, would be of interest. The method of determining the natural frequencies and decrements for any particular relay burden and device has been given and an example has been worked out in the section headed, "Transient Performance—Series Circuit". Also, the values for a number of specific burdens and devices have been given in the oscillograms and summarized in table II. A considerable amount of similar typical transient test information had been included originally in the paper but it was necessary to delete this information because of space limitations. Summarizing the steps involved in determining the transient performance in any particular case:

1. Determine the constants of the device for the particular adjustment and of the connected burden and reduced to an equivalent series circuit as shown in figure 2.

2. Determine whether oscillatory or nonoscillatory, based on whether R^2 is less or greater respectively than $4\,L/C$.

3. If nonoscillatory, the time constants should be determined from equations 35 and 36, the time to crest from 38 and the crest value or overshoot from 39. This is based on the primary voltage falling to zero.

4. In case the circuit is oscillatory the natural frequency would be determined from equation 41, the ratio of successive peaks or the decrement from 43, and the first peak in the case of pure resistance burden from 44.

For the more complicated burdens and connections the a-c network calculator provides the most convenient method of solution.

Mr. Kennedy has expressed surprise that the term Z_x could be ignored in the transient analysis. It is true that to be perfectly general this term should be included. However, for the device described the exciting impedance is very high compared with the tap-capacitor impedance. It is only when saturation occurs that this impedance would fall to low enough value to affect results. The specially designed transformers used with the devices described in the paper operate at flux densities sufficiently low that saturation does not occur even under transient conditions. Tests on complete three-phase devices substantiate these conclusions.

4. Mr. Higgins has presented an interesting circuit utilizing two damping resistors, one in parallel with the transformer secondary and the other in parallel with the burden. Early in our development an analysis was made of these possibilities and it will be of interest to show from the theory given in the paper the results to be expected. Considering a high-power-factor burden such as a pure resistance, it is evident that the connection of a second resistor in parallel will lower the total R of the circuit and as shown in equation 43 will increase the ratio of successive peaks, which is opposite to the desired effect. Also since R^2 is smaller compared with $4L/C$, the circuit tends to become more oscillatory than before. With pure inductive burden, damping resistance at this location will introduce loss in the resonant circuit and reduce the ratio of successive peaks. Obviously actual burdens will generally fall between these two limits, but our analysis has indicated that down to quite low power factors the net effect is unfavorable.

The resistance in parallel with the transformer secondary will exercise a pronounced damping effect on the resonant circuit since it is connected across the high-voltage point of this circuit. However, it will also make the impedance Z_{acx} shown in figure 2*d* of the paper a resistance-capacitance branch rather than nearly pure capacitance. As a result it cannot be neutralized by the reactance Z_p and, therefore, the vector $I_b Z$ (figures 3*a*, *b*, *c*) becomes relatively large. The resulting steady-state performance of the device is affected as it is no longer a "stiff device". Changes in burden cause relatively large ratio and phase-angle variations. This will be especially important when both star and residual burdens are supplied from the same set of devices. The star voltages, although adjusted correctly for balanced conditions, will be in error under fault conditions which involve residual voltage. This is explained in appendix II of the paper. These effects may be small enough so as not to be objectionable in some applications.

5. Mr. Powel has very nicely summarized the main points brought out in the paper.

Progress of the Art in Electrical Machinery—1934–39

THIS REPORT on the progress of the art in electrical machinery covers the five-year period from 1934 to June 1939.

D-C Machinery

There have been no radical changes in the design of d-c machinery for many years. Since the advent of the commutating pole, development has been almost entirely to extend the limits of performance along known lines.

There has been a slow extension of the speed of the machines, particularly the exciters and dynamometers. The speed of dynamometers both in revolutions per minute and peripheral velocity has been higher than that of the exciters. The reason for this is that although the dynamometers are all capable of operating at high speeds, in actual practice they run very little at the top speeds. For exciters, the peripheral speeds of the cores of machines in service have reached 13,000 feet per minute with 10,000 feet per minute on the commutator. One manufacturer is now building 3,600-rpm exciters having a peripheral of 15,000 feet per minute.

There is evidence for need of development of d-c motors which can be started across the line. At the present time, the practical limit of 230-volt compound motors is about 7 1/2 horsepower at 1,750 rpm and in the 550-volt motors, the compound-wound three-horsepower is about the limit. Shunt-wound motors that may be line-started are very much smaller. There seems to be a definite need for the extension of line-starting practice to larger machines as soon as designs will permit.

On the adjustable-speed motors, that is, motors whose speed is controlled by weakening the field, the present maximum ratio is six to one. Most adjustable-speed applications are served by a four-to-one range. Reversing planers and certain other special applications have been successfully served for several years by six-to-one speed range by field weakening.

The use of glass insulation is being tried on various applications for d-c motors. At the present time, there has been no report of any pronounced disadvantage in the use of this type of insulation.

Transformers

Insulation impulse tests have been established, and levels for guarantees and tests proposed for use by the industry. This work is probably one of the principal features for this period. It is not yet quite complete as levels for steep-wavefront testing have not been established.

The standardization of transformer ratings on the basis of temperature rise without reference to ambient temperature has been proposed and very generally accepted.

Considerable progress has been made in recommending additions to the material given in AIEE Standard No. 100 entitled "Recommendations for the Operation of Transformers," dated 1930. These additions include curves for short-time overloads (1) for recurrent conditions and (2) for emergency conditions ranging in time from a few seconds (short circuit) to several hours. As a rough guide for operating by oil temperature, oil temperature limits are given for various loads.

This work has resulted in the adoption of a pamphlet entitled "Guides for Operation of Transformers" which is to be incorporated as an appendix to the Proposed American Standards for Transformers, Regulators, and Reactors" to be published soon by the American Standards Association. The work on these operating recommendations is being continued in order to determine whether different recommendations should be made for transformers operated with expansion tanks or with inert gas above the oil level.

The question of the possibility of operating transformers at higher temperatures when excluding oxygen from the oil by the use of an inert gas cushion, or the use of an expansion tank (conservator) has been under discussion. Further consideration may show that by excluding oxygen from the oil, higher temperatures may be permissible.

Mercury-Arc Rectifiers

The use of the multianode metal-tank mercury-arc rectifier is well established in several fields. There are at present approximately 500,000 kw of this type of rectifier in operation on railway properties in America. The units vary in capacity from 500 to 3,000 kw and in voltage from 500 to 3,000 volts direct current.

The outstanding railway rectifier installations recently finished and put in operation include the San Francisco-Oakland Bay Bridge Railway, where 20,000 kw of rectifier capacity was installed for voltages of 600 and 1,200 volts direct current and capacities up to 2,500 kw per unit; and for the City of Philadelphia for heavy-duty subway service, consisting of two 3,000-kw 630-volt rectifiers.

In recent years, the mercury-arc rectifier was introduced in electrolytic plants. Some of the larger installations were for chlorine, sodium, and aluminum production. At present, there are in use in this country over 175,000 kw of rectifier capacity supplying this industry. One of these plants has 20 rectifiers with a total capacity of 55,000 kw. These were put in commercial service in the latter part of February 1938.

Due to the fact that a concentration of 55,000 kw of rectifiers in one substation became a major load of the supply network, it became necessary to reduce the influence of the harmonics on neighboring communication systems. In order to overcome this difficulty, an arrangement was used which provided phase displacement of each unit, by means of auto-transformers, by different amounts in order to increase the effective number of rectifier phases. The installation, considering all units as a whole, operates as a 60-phase system, and the harmonic currents generated by the rectifiers in the a-c network were reduced to such an extent that the effect of the rectifier load on the power and adjacent communication systems was practically eliminated.

Paper 39-135, prepared by the AIEE committee on electrical machinery, recommended by the AIEE committee on electrical machinery, and presented at the AIEE combined summer and Pacific Coast convention, San Francisco, Calif., June 26–30, 1939. Manuscript submitted April 24, 1939; made available for preprinting May 10, 1939.

AIEE Electrical Machinery Committee, 1938–39: C. M. Laffoon, *chairman;* J. L. Hamilton, vice-chairman; P. L. Alger, J. E. Clem, J. H. Cox, C. M. Gilt, I. W. Gross, M. S. Hancock, F. R. Harrell, A. P. Hayward, C. C. Herskind, F. Ellis Johnson, L. A. Kilgore, O. K. Marti, V. M. Montsinger, T. H. Morgan, S. H. Mortensen, F. L. Moser, C. A. Muller, J. R. North, F. D. Phillips, H. V. Putman, P. H. Rutherford, C. C. Shutt, J. B. Swering, H. D. Taylor, B. R. Teare, B. Van Ness, Jr., and G. A. Waters.

Subcommittees and Chairmen, 1938–39: Induction machinery, G. A. Waters; transformer, F. J. Vogel; rating of electrical machinery and apparatus, F. R. Harrell; synchronous machinery, H. D. Taylor; test code for fractional-horsepower motors, J. L. Hamilton; mercury-arc-rectifier, O. K. Marti; d-c electrical machinery, M. S. Hancock; insulation-resistance, J. B. Swering.

This illustrates an inexpensive means of reducing the effect of rectifier harmonics by utilizing the large number of anodes available in a large installation for increasing the number of phases.

Development work has been done toward perfecting the use of energized grids to obtain voltage regulation, and to obtain rapid extinction of the arc during abnormal conditions such as short circuits and arc backs. By applying a negative potential to the grids, current from properly functioning anodes may be blocked and prevented from feeding into a fault, and by the use of auxiliary electronic tubes, or high-speed relays, this type of arc extinction may be accomplished in the order of one cycle.

The need for heat exchangers to overcome the corrosion problem in steel-tank mercury-arc rectifiers has been eliminated for many cases by soldering or welding copper cooling coils to the tank walls. Of course, this method does not eliminate heat exchangers where the water available deposits a prohibitive amount of scale, necessitating straight tubes for mechanical cleaning.

The ignitor type of rectifier, or ignitron, constitutes the most radical departure from conventional practice in America during the past few years. Considerable attention has been given throughout the world to single-anode tank mercury-arc rectifiers, and the ignitron belongs to this class. This type of tube makes use of an ignitor which starts the arc in a tube by forming a cathode spot or a pool cathode at the beginning of each conducting period for a particular anode and permits the arc to extinguish during the nonconducting period. This type of operation has permitted the location of the anode directly over and relatively close to the cathode, with a reduction in the amount of shielding. This results in an appreciable reduction in arc voltage. Control of voltage, and arc extinction during faults, is accomplished by operating on small auxiliary thyratron tubes in the ignitor circuit, which control the time of firing.

Ignitrons are now in service in various industries. There are 13 units in mining service at 275 and 600 volts and in capacities from 300 to 500 kw. In electrochemical service, there are seven units at 280 and 600 volts and with capacities from 200 to 1,000 kw, and in railway service, there are two 600-volt 3,000-kw units. These latter have an anode rating equal to that of the largest multianode rectifier.

Recently, some units of permanently evacuated pumpless rectifiers have been installed, for lower-capacity requirements, at both 250 and 600 volts. Some of these are multianode glass-bulb mercury-pool rectifiers; some are metal-tank single-anode ignitrons; and others are metal-tank thermionic cathode phanatrons. These sealed-off rectifiers are attractive for small-capacity requirements because of the absence of vacuum-pumping auxiliaries. However, the need for periodic replacement must be balanced against objections associated with continuously operating vacuum auxiliaries.

Table I

Number	Kilovolt-Amperes	Kilowatts	Customer	Manufacturer*	Date Installed
2	25,000	20,000	Louisiana Steam Generating Co.	W	1938
1	29,500	25,000	Connecticut Light and Power Co.	W	1938
1	31,250	25,000	Gulf States Utilities Co.	W	1938
1	35,000	20,000	Kansas Gas and Elec. Co.	W	1938
1	37,500	30,000	Boston Edison Co.	W	1939
1	25,000	20,000	Metropolitan Edison Co.	W	On order
1	43,750	35,000	Iowa Power and Light Co., Des Moines	AC	1938
1	31,250	25,000	Central Illinois Public Service Co.	AC	1938
1	25,000	20,000	Southern Indiana Gas and Elec. Co.	AC	1938
1	25,000	20,000	Madison Gas and Elec. Co.	AC	1938
1	18,750	15,000	City of Springfield, Ill.	AC	1938
1	31,250	25,000	Central Illinois Public Service Co.	AC	On order
1	31,250	25,000	Public Service Co. of Colorado	GE	1937
1	28,571	20,000	United Power Mfg. Co.	GE	1937
1	35,000	25,000	Monongahela West Penn Public Service Co.	GE	1937
1	25,000	20,000	N. Y. State Elec. and Gas Corp.	GE	1938
1	50,000	40,000	Hartford Elec. Light Co.	GE	1938
1	25,000	20,000	Ohio Edison Co., Mad River	GE	1938
1	37,500	30,000	Potomac Edison Co.	GE	1938
1	25,000	20,000	Public Service Co. of N. H.	GE	1938
1	25,000	20,000	Public Service Co. of Okla.	GE	1938
1	42,857	30,000	City of Jacksonville, Fla.	GE	1939
1	28,571	20,000	Houston Lighting and Power Co.	GE	1939
1	31,250	25,000	Consolidated Gas Elec. Light and Power Co. of Baltimore	GE	On order

* W—Westinghouse Electric and Manufacturing Company; AC—Allis-Chalmers Manufacturing Company; GE—General Electric Company.

Turbine Generators

The two principal items of progress in turbine generators during the past few years are (*a*) the development of the two-pole 3,600-rpm unit for ratings required by the central-station industry, and (*b*) the application of hydrogen as the cooling medium.

The use of higher temperatures and pressures has greatly increased the range of capacities of the higher-speed units into the field formerly held by 1,800-rpm units or even of 1,200-rpm units.

The higher rotational speed makes it possible to use smaller physical dimensions and weights for the turbine. This simplifies the design and construction problems introduced by the use of high pressures and temperatures of the steam.

Large-capacity air-cooled, 3,600-rpm turbine generators on order or in service are listed in table I.

The advantages of hydrogen as a cooling medium for turbine generators are:

1. Reduced windage, friction, and ventilating losses, because of the low density of the hydrogen gas. The ventilating losses are proportional to the gas density. Full-load efficiency of the generator may be 0.6 per cent or more higher than for the corresponding air-cooled machine.

2. Increased output per unit volume of active material, because of the high heat-storage capacity, thermal conductivity, and heat-transfer coefficients of hydrogen. This advantage of hydrogen cooling makes it possible to build turbine generators for higher ratings than are possible with air cooling.

3. Reduced maintenance expense, because of the freedom from dirt and moisture.

4. Increased life of the insulation on the stator winding, because of the absence of oxygen and moisture in the presence of corona.

5. Reduced windage noise, because of the low density of the gas.

Hydrogen-cooled turbine generators either in service or in manufacture are listed in table II.

With operating experience on a number of units and over a considerable period of time at hand, the initial stage of development of hydrogen-cooled generators is passed. There will no doubt be minor difficulties to correct as time goes on, but these will be of no more serious nature than are to be found in air-cooled generators. It will also be possible to simplify considerably the generator and its attendant parts in future machines as greater experience is gained with this

Table II

Number	Kilovolt-Amperes	Kilowatts	Customer	Manufacturer*	Date Installed
3,600-rpm units					
1	50,000	45,000	West Penn Power Co.	W	1938
1	58,889	53,000	Consolidated Edison Co. of N. Y., Inc.	W	1938
1	58,750	50,000	Philadelphia Elec. Co.	W	1938
1	43,750	35,000	Cincinnati Gas and Elec. Co.	W	1938
1	81,250	65,000	Consolidated Edison Co. of N. Y., Inc.	W	On order
1	43,750	35,000	Pa. Power Co.	W	1939
1	43,750	35,000	Columbus and Southern Ohio Electric Co.	W	1939
2	43,750	35,000	Georgia Power Co.	W	On order
1	43,750	35,000	Pa. Elec. Co.	W	On order
1	18,750	15,000	Wis. Elec. Power Co.	AC	1938
1	31,250	25,000	City of Lansing, Mich.	AC	On order
1	31,250	25,000	Dayton Power and Light Co.	GE	1937
1	50,000	40,000	American Gas and Elec. Co., Logan, W. Va.	GE	1937
2	66,667	60,000	American Gas and Elec. Co., Windsor station	GE	1—1939 1—On order
1	58,889	53,000	Consolidated Edison Co. of N. Y., Inc.	GE	1938
1	37,500	30,000	New Orleans Public Service Co.	GE	1939
1	55,555	50,000	Public Service Elec. and Gas Co.	GE	1938
3	43,750	35,000	Consumers Power Co.	GE	On order
1	28,125	22,500	Ind. and Mich. Elec. Co.	GE	On order
3	50,000	40,000	Pacific Gas and Elec. Co.	GE	On order
1	50,000	40,000	Virginia Elec. Power Co.	GE	On order
2	50,000	40,000	Duke Power Co.	GE	On order
2	62,500	50,000	Public Service Elec. and Gas Co.	GE	On order
1	62,500	50,000	Philadelphia Elec. Co.	GE	On order
1	81,250	65,000	Consolidated Edison Co. of N. Y., Inc.	GE	On order
1,800-rpm units					
1	75,000	60,000	Duquesne Light Co.	W	1938
1	176,470	150,000	Chicago District Elec. Generating Corp.	GE	1937
1	81,250	65,000	Cincinnati Gas and Elec. Co.	GE	1938
2	68,750	55,000	Ford Motor Co.	GE	1939
1	60,000	54,000	Ind. and Mich. Elec. Co.	GE	On order
1	100,000	80,000	Central N. Y. Power Co. (Oswego)	GE	On order

* W—Westinghouse Electric and Manufacturing Company; AC—Allis-Chalmers Manufacturing Company; GE—General Electric Company.

type of machine. Cost of supplying hydrogen gas is very low, and it has been the experience in most stations that the additional attention on the part of the operators as compared to that for an air-cooled machine is very small. Hydrogen cooling will probably be adopted more and more for units of 30,000 kw and above where the additional cost of the gas-tight housing and gas control can be justified economically.

Synchronous Condensers and Motors

A novel synchronous condenser rated 25,000 kva at 3,600 rpm (W)* has been built for the American Gas and Electric Company with hydrogen cooling, and excitation from an ignitron rectifier. A 50,000-kva 50-cycle 600-rpm hydrogen-cooled synchronous condenser (W) was furnished the Southern California Edison Company. The design of this condenser permits operation at 60,000 kva and 60 cycles. Two 30,000-kva 1,200-rpm hydrogen-cooled synchronous condensers (GE)† were supplied to the City of Seattle and the Ohio Power Company, respectively, during the year, and very recently a 60,000-kva, 600-rpm hydrogen-cooled condenser (GE) has been ordered by the City of Los Angeles. Air-cooled condensers (AC)‡ rated at 15,000 kva, 900 rpm, and 20,000 kva, 720 rpm were furnished the Memphis Power and Light and the Illinois Northern Utilities Company respectively. A 25,000-kva condenser (W) was installed at the Massena plant of the Aluminum Company of America in 1937. A similar 15,000-kva air-cooled condenser (W) is now on order for the Florida Power and Light Company.

Three vertical-shaft synchronous motors out of an order for six were installed for the Metropolitan Water District of Los Angeles, rated 12,500 horsepower, 450 rpm (W), built for exceptionally severe starting duty; these are similar to machines rated 9,000 horsepower, 400 rpm (GE) and 4,300 horsepower, 327 rpm, (AC) previously installed on the same water supply project. In marine work, two turbine-electric tankers of unusual interest were placed in service by the Atlantic Refining Company, the *J. W. Van Dyke* and the *Robert H. Cooley*, each with a main-drive synchronous motor rated 5,000 horsepower, 90 rpm supplied with power by a turbine-generator of 4,500-kw capacity (GE), the output of the generators being used when in port for driving pumps for rapid loading and unloading.

* Westinghouse Electric and Manufacturing Company.

† General Electric Company.

‡ Allis-Chalmers Manufacturing Company.

Electric Couplings

Electric couplings are now coming into general use in geared ship-propulsion installations to provide the necessary flexibility to protect the gears from torsional vibration from the engine. In addition, they limit shocks in the system by having a definite maximum torque which they will transmit, this torque being independent of speed. They also can be disconnected instantaneously by interrupting their field current.

In construction, the form generally used consists of a salient-pole field member excited by direct current and a secondary member similar to that used on an induction motor. The secondary rotates with the field except for a small slip.

At the present time, one tanker has been equipped with two 700-horsepower (Elliott) couplings and there are on order 68,000 ship horsepower (W) in 24 couplings for use on vessels being built for the United States Maritime Commission.

Induction Motors

There has been a material increase in the number of high-speed induction motors built for high-pressure pump applications. The ratings of two-pole 60-cycle induction motors have reached 2,500 horsepower.

The noise level of high- and moderate-speed motors has been reduced to the point where it is well below that of a modern power house.

Explosion-resisting motors of cast or fabricated construction are now being built for ratings up to 600 horsepower, 3,600 rpm. Glass insulation is playing a part in the development of these motors.

The completion of two 1,000-horsepower 3,000-rpm totally enclosed motors (GE), ventilated by carbon-dioxide gas circulating through surface coolers, marks an important new trend in this field. This design provides security against explosion risks in sizes larger than can conveniently be made of the heavy explosion-resisting construction.

Frequency Converters

A 20,000-kw variable-ratio frequency changer (GE) of the Scherbius type built during the year was unusual in having the Scherbius equipment on the 60-cycle end. The induction machine of this set is a wound-rotor type with 24 poles, rated 27,000 kva, 300 rpm, 13,800 volts,

and is designed for 0.8 power factor over-excited operation with a slip adjustable over a total range of one cycle. A 60,000-kva, 50–60 cycle 600-rpm hydrogen-cooled frequency changer (W) was built for the City of Los Angeles and installed late in 1936.

Water-Wheel Generators

Most of the available water-power sites which are economically important from the standpoint of electric-power production and disposition alone have been developed. The majority of the hydroelectric developments that are being undertaken at the present time are justified economically for the production of electrical energy only when considered in connection with irrigation, flood control and navigation, or a combination of these factors. Undertakings of such broad scope are necessarily of a public nature and consequently have been carried on as complete or partial-public or governmental enterprises.

The principal improvement in the hydraulic turbine has been the development of the adjustable-blade propeller to improve the efficiency performance of the turbine under different water flow conditions. No major changes have been required or made in the design of generators driven by this type of prime mover.

A large number of hydraulic turbine driven generators has been purchased or placed in service. Two more Boulder Dam units rated 82,500 kva, 180 rpm (GE) were tested and placed in service, and two others (W) were built and ready for installation. The City of Los Angeles has purchased two additional 82,500-kva units (W) for installation at Boulder Dam. At Bonneville Dam two 48,000-kva 75-rpm generators (GE) were installed, and two more rated 60,000 kva (GE) were on order. For the Tennessee Valley Authority developments, two 40,000-kva 81.3-rpm units (W) went into service at Pickwick Dam; three rated 27,000 kva, 69.2 rpm (GE), under construction for Guntersville, have the distinction of having the largest diameter and highest overspeed of any generator so far designed of the overhung type; for the Hiwassee Dam, one 64,000-kva 120-rpm unit (W) has been ordered; and three units of 30,000 kva 75 rpm (AC) have been ordered for Chickamauga Dam. Interesting units for export include two horizontal machines of unusually high speed, rated 10,118 kva, 500-rpm, 25 cycles (GE) built for the government of Mysore, India, and three vertical machines rated 70,000 kva, 125 rpm (W), on order for the Sungari River development in Manchukuo. Among recent orders are the three 108,000-kva 120-rpm machines (W) for Grand Coulee, these having larger dimensions than the famous Boulder Dam units; and four rated 75,000-kva, 120 rpm (GE) for the Shasta development of the Bureau of Reclamation. Two 34,000-kva 120-rpm units (GE) and two 34,000-kva 120-rpm units (W) are under construction for Santee Cooper. Four 16,000-kva, 150-rpm units (W) for Grand River have been shipped. Four 20,833-kva 138$^1/_7$-rpm units (W) for Appalachian Electric Power Company have been shipped. One 27,500-kva 120-rpm unit (W) has just gone into service on the property of Anglo Newfoundland Development Company.

Electrical Engineering and the Petroleum Refiner

G. R. WEEKS
NONMEMBER AIEE

H. W. GIESECKE
ASSOCIATE AIEE

C. M. LATHROP
NONMEMBER AIEE

THE object of this discussion is to present a brief history of the use and development of electric power in the oil-refining industry and to indicate how refinery design and operation have been affected by recent developments in electrical engineering.

An oil refinery consists of equipment for the receipt and storage of crude oil, apparatus for converting it into salable petroleum products, and additional storage and distribution facilities for the finished products. The first and last of these classes of equipment are composed largely of tanks, piping, and pumps. In the second category is the refinery proper, which may be compared to a shop containing many machines, the refinery being composed of various processing units, each of which performs a definite task upon a certain crude or previously processed feed stock. The most important of the units carry out the process of fractional distillation, obtaining numerous products ranging from heavy tar or coke to light highly volatile hydrocarbons. Fractionation is often combined in a given unit with the supplementary processes of cracking, polymerization, etc.

A typical distillation unit consists of one or more furnaces, a battery of pumps, fractionating towers, smaller pressure vessels, heat exchangers, condensers, etc. Many of these units operate under pressure and temperature conditions comparable to those encountered in modern boiler plants.

Other units are required to condition the products of the fractionating process for sale; these consist of stabilizer plants, chemical treating plants, blending units, dewaxing plants, etc. A third type of unit is the by-product plant which may produce anything from insecticide to compounds used in cable insulation. In addition to the refinery proper there must be auxiliary plant equipment for supplying steam, electric power, compressed air, repair and construction services, office facilities, etc.

Safety Precautions to Be Observed

The refining of petroleum involves the safe handling of inflammable and corrosive liquids and gases. The major part of refinery electrical equipment is therefore designed to be suitable for use with equipment performing such operations. Suitable electrical equipment is approved by the Underwriters' Laboratories for use in what is termed class 1, group *D*, hazardous locations.

Apparatus, to be classed as explosion resisting, must be designed so that it is not possible for an internal ignition of explosive vapors to be propagated to the outside atmosphere. Sturdy cases with ground-joint heavily bolted flanged covers are required or the apparatus must be deeply immersed in suitable steel tanks filled with oil. Screwed joints must have at least five tight threads. Conduit entrances to spark-producing apparatus must be sealed with compound in an approved sealing chamber to prevent propagation of an explosion along the conduit

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G. R. WEEKS, H. W. GIESECKE, and C. M. LATHROP are employed by the Standard Oil Development Company, Elizabeth, N. J.

system; long conduit runs are sealed at intervals for the same purpose.

The presence of sulphurous gases, furnace smoke, and salt air (since many refineries are located on seacoasts) makes it necessary to use porcelain insulators of much higher rating than the service voltage—15,000-volt insulators are commonly used for 2,300-volt service. In addition, all electrical apparatus must be protected to the greatest possible degree against corrosion, or designed of suitable materials to withstand the corrosive effect.

Type of Load

The refinery load is one that usually offers a unique opportunity for economical power generation. Waste refinery products are generally available as a cheap fuel in both liquid and gaseous forms, the need for process steam makes possible an economical station heat balance even with a restricted supply of condensing water, the use of dual steam-electric-driven pumps and other equipment furnishes a means of adjusting the heat balance, and finally and perhaps of most importance, the high percentage of the generated power used for driving synchronous motors and fully loaded induction motors which operate for long periods without shutdown makes for high load factors and high power factors. Continuous operation of a refining unit for 30 days is not unusual and runs of six months or longer are expected for some processing operations. There are seasonal variations in total load on the generating equipment due to seasonal variations in demand for various products (see figure 1), however, these are not ordinarily so great that an economical heat balance cannot still be maintained. Daily load variations are very small since the lighting load is small and the power load is continuous.

Steam and Compressed Air

Process steam is generally supplied to the refinery from the boiler plant at pressures in the vicinity of 125 pounds gauge, and is used in considerable quantities for supplying distillation heat, for oil-burner atomization, stripping operations, and for gas freeing of equipment. Certain engines and turbines are steam driven from the 125-pound mains for driving fans, pumps, and compressors, especially in older units. These units usually exhaust to the low-pressure steam main at about 10 pounds pressure. Such low-pressure steam is used in heating buildings and heavy-oil storage tanks, and is also employed to maintain a low viscosity in pipe lines circulating heavy oil through the refinery by carrying a small steam line next to the oil line under an insulating jacket. Steam is also used to some extent for fire protection.

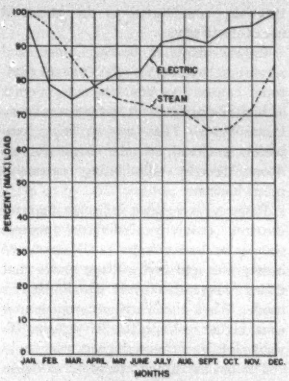

Figure 1. Monthly variation of steam and electrical load in a refinery

A supply of compressed air is necessary for the pneumatic tools used in refinery maintenance. At every "turn-around" or shutdown period, the tubes of tubular furnaces are cleaned by air-driven tools. Drills, grinders, tube-expanders, jack-hammers, and riveters, are in use. The necessary compressed air is supplied in the typical refinery by synchronous-motor-driven compressors of large size.

Electric Power

The introduction of high-pressure high-temperature steam equipment for industrial power-plant application and the development of the high-back-pressure turbine made refinery engineers more conscious of the merits of electric drive, especially from the standpoints of economy of operation and saving of space. The type of mechanical equipment used in refineries then underwent major changes as manufacturers of this equipment were called upon to develop new and entirely different apparatus than was used hitherto.

The high-back-pressure turbine was much in demand when first introduced as it supplied the large quantities of medium-pressure steam for driving slow reciprocating pumps and other relatively inefficient processing equipment. Then, as the opportunity occurred to replace worn out and inefficient steam equipment with electric drive, the need for large amounts of medium pressure steam decreased and correspondingly, the requirements for electric power increased with the result that use of condensing turbine again became practicable. However, the high-back-pressure turbine was soon followed by the very flexible bleeder-condensing turbine so that today the refinery engineer may select from a wide range of equipment to give him an efficient power plant tailored to fit the scheme of operation of his particular refinery.

The most popular generating voltage is 2,400 volts because it has a wide economical range of uses without transformers together with very good distribution characteristics. Other voltages such as 6,900 and 13,200 volts are being used in individual cases for specific reasons such as long-distance distribution which might be necessary for a very large refinery.

With the increase in power used at 2,400 volts, a new class of switching equipment had to be developed to handle safely the increased capacity generated at what today is considered a low voltage. This equipment had to embody the safety principles of utility-company equipment and yet be reasonably low in first cost. Such equipment is the present-day medium-interrupting-capacity. short-time high-current-carrying-capacity high-speed oil circuit breaker with high-speed relays, all factory assembled in dead-front steel cubicles. Still a further development necessitated by the high currents in the present large low-voltage generating station was improvement in bus design, so that electrical engineering borrowed from structural practice the angle, channel, and box designs that we have today. The larger stations have main and synchronizing busses with reactor protection between generator bus sections or bus sectionalizing reactors to limit short-circuit currents to a reasonable figure in order to make use of economical types of switchgear.

Distribution System

A refinery distribution system is required to supply substations that are located to serve the different operating areas or load centers. In a large refinery, units are continually being added to or withdrawn from the refinery system so that the load centers are continually changing. The basic distribution scheme therefore must have maximum flexibility to meet the ever-changing requirements.

Depending on the size and layout of the particular refinery and its power sources, loop, radial, or combination loop-radial systems are used for the high-voltage

distribution. The processes are such that a definite closely knit load center can be established for each unit, thus tending to simplify the secondary-distribution problem.

Overhead lines have been widely used for high-voltage distribution, but refineries are now following the modern trend to underground construction. This is highly advantageous from the standpoints of safety, reliability of service, and clearing the air to allow freedom in fighting fires, moving cranes, etc. Overhead distribution is retained where the economics of the situation so dictate. Substations are required to supply high voltage directly to feeders for large motor-driven compressors and pumps, to transformers for 440-volt power distribution to small- and medium-size motors, lighting transformers, and numerous miscellaneous services.

A typical substation consists of a small building and adjoining fenced-in transformer enclosure.

Substation switchgear in older installations was of the pipe-frame and panel type with panel-mounted instruments and controls and oil circuit breakers pipe-frame mounted behind the panels. Such equipment is being superseded by metal-clad and steel-cubicle-type switchboards in new construction; advantages being greater safety to personnel, greater reliability due to enclosure of bus bars and control circuits, and smaller space requirements.

Motors

Advances in pump design have been of great importance to refinery power engineers since this type of load far exceeds any other. Slow-speed reciprocating pumps with high steam consumption have been replaced to a great extent by high-speed space-saving centrifugal pumps with efficient direct-coupled motor drive.

When such pumps were first used in refineries, they were driven by open motors and the motors and pumps were separated by fire walls. Fire walls do not completely eliminate the fire hazard in all cases and are expensive and inconvenient in any case. The explosion-proof totally enclosed motor has been developed until today this type of motor is standardized in sizes up to 350 horsepower. It is reasonable in first cost and the maintenance on this type is far less than was experienced with the open type.

The extension of explosion-proof motors to include gearmotor and close-coupled motor and pump units has substantially contributed to the increased use of electricity.

Improvements in bearings, fans, and insulation have been applied to explosion-proof motors to enable them to operate at high temperatures in corrosive refinery atmospheres. These motors, being completely enclosed, can be mounted outdoors, thereby eliminating expensive pump houses.

Refinery experience indicates that for greatest economy individual motors should be low voltage (440) up to 75 horsepower and high-voltage above that rating where 2,400-volt distribution is used. When the distribution system is at a higher voltage the horsepower dividing line is, of course, higher.

The uninterrupted operation of essential pumps while the unit is "on stream" is of extreme importance to the refinery operator. In this case a dual drive is frequently used, that is, the centrifugal pump has the impeller shaft extended through both ends of the casing, one end being coupled to a motor and the other end to a steam turbine. If the motor full-load speed is 3,550 rpm, an automatic valve would be set to admit steam to the turbine at about 3,500 rpm. Should there be a power failure or other fault in the electric drive the turbine would automatically take the load until the motor could be again brought into use.

Individual enclosed induction motor units as large as 1,250 horsepower at 3,600 rpm have been developed for use in refining areas, the enclosures are of heavy steel plate, and cooling is accomplished by means of water coils mounted within the enclosures. The enclosures are air-tight except for the shaft opening and are filled with inert gas at a pressure higher than atmospheric. The use of such motors is being extended to slightly or occasionally gaseous areas by omitting the inert-gas protection.

Synchronous motors are used in refinery work to a considerable extent for driving reciprocating compressors. These are used for air, refrigeration, and hydrocarbon gases.

The ease with which low-speed salient-pole synchronous motors may be designed and operated is the chief reason for their selection for compressor drive. In many instances the motor is installed between cranks of duplex machines in a manner analogous to the installation of shaftless induction motors in power tools, giving a valuable saving in space together with desirable mechanical characteristics. Compressor motors are usually large enough to require connection to the refinery high-voltage system but are not so large as to prevent full-voltage starting.

Where inflammable gases are handled or where refrigeration machinery is located in proximity to petroleum vapors, the motors are protected by fire walls or enclosed in an airtight steel casing with cooling air brought in through a duct from a gas-free area. Air is forced through the duct with an explosion-proof motor-driven blower having its starter interlocked with the compressor motor starter so that fresh air is supplied to the compressor motor before it can be started.

Motor Control

To obtain widest benefits from the previously discussed motor developments, it was necessary to obtain starting equipment especially designed for refinery service. Small low-voltage motors use standard air-break motor starters enclosed in cast-iron explosion-proof housings. Larger low-voltage motors are controlled by deep-oil-immersed starters of the across-the-line type. Satisfactory relays of both thermal and magnetic types have been developed for use under oil so that such equipment includes all features of non-oil-immersed equipment. Since the refinery distribution system is designed to carry large blocks of power, low-voltage motors are line starting except for a few of the largest sizes in refineries using distribution voltages above 2,300. Such starters are considered special.

The latest practice in motor control requires an air circuit breaker of the "arc dissipating" type in an explosion-proof housing at the motor branch junction. This breaker is depended upon for short-circuit protection and also serves as a disconnect.

An alternate practice is the use of oil-immersed starters combined in the same enclosures with oil-immersed fused switches. The necessary fuses are individually air sealed to prevent oil from interfering with their proper operation.

Since high-voltage motors are fed directly from a substation, the motor control equipment is usually located in the substation and is installed as a component part of the substation cubical switchgear. Approximately 50 per cent of these starters are required to be reduced-voltage type. Since such switchgear is required to have up to 50,000 kva interrupting capacity, the starter contactors are similar to modern oil circuit breakers in design. Remote push-button control is also used with these starters. As a late development the high-voltage starters are being constructed explosion re-

sisting for certain locations, such starters have oil-tight circuit-breaker-type tanks and open-air-type control equipment under a diving bell immersed in oil.

The necessary breakers and starters for all the motors, other than high-voltage motors, in a given refinery unit are usually grouped in a switch house and mounted upon racks. The switch house may be a simple roofed structure without sides, usually enclosed in chain-link fencing. The starters are push-button operated from explosion-proof push-button stations located at the motors and/or in the unit control room.

Instruments

For proper operation, the temperature at a multitude of points in the unit must be indicated at the unit control house so that liquid flow in various lines may be adjusted to maintain process requirements. To observe temperature conditions at the hundreds of necessary points and to correlate this information at necessary intervals would be a Herculean task in itself were it not for the use of recording pyrometers. Resistance bulb thermometers are in limited use but the majority of temperatures are measured by iron-constantan thermocouples. These and other types of instruments are motor driven. Instruments which may be rated explosion resisting are a current development.

While the total electric load developed by such instruments is not large, the instruments of an oil refinery do represent a problem in maintenance and in investment cost.

Automatic regulation of oil flow in certain lines in accordance with unit temperature conditions is obtained from instruments. This requires the use of electrically operated valves ranging in size from fractional-inch solenoid valves to large-size motor-driven valves.

Shops

Oil refineries are usually equipped to maintain and repair equipment. The extent to which repair equipment is installed depends in a large degree upon the location of the refinery and the availability of adequate industrial facilities in the vicinity.

Where the quantity of the work permits, a refinery will have foundry, boiler, machine, blacksmith, carpenter, electrical, instrument, and pipe shops, all of which require electrical power. This load is supplied by 440-volt three-phase lines.

Welding

In recent years, following improvements in welding technique, the scheme of certifying approved welding personnel, and the application of radiography, the use of welding in the oil industry has increased rapidly and we now have welded tankage, pressure vessels, piping for pressures up to 1,500 pounds, structures, pipe supports, etc. Welding is also used for applying stainless-steel linings to pressure vessels. The proper technique has been developed for welding the various chromium and nickel steel alloys which are commonly used for refinery piping. At present there appears to be no phase of refinery construction to which welding may not be applied. Refineries are now commencing to install complete systems of three-phase 440-volt welding outlets for operating portable motor-generator welding sets. These outlets are of explosion-proof construction having a switch (or circuit breaker) and interlocked receptacle. Refinery metal-working shops are usually provided with welding equipment.

Lighting

On most installations less than five per cent of the refinery load is composed of electric lighting. Lighting fixtures for use in processing areas are of the vapor-proof type with heavy glass globe and guard. Anodized-aluminum reflectors are used with such units when installed on the top level of structures, platforms, walkways, etc. Floodlights are installed on the equipment structures to illuminate the general ground areas in the immediate vicinity of the units.

Modern refinery design calls for the following lighting intensities:

Location	Foot-Candles
Control rooms	10 to 15
Pump rooms, switch houses	6 to 8
Main operating platforms	6 to 8
Yard areas and ordinary platforms	2 to 4

These intensities have tended to make work and maintenance around the units safer. This would not have been possible but for the fact that manufacturers developed suitable switches, plug receptacles, and conduit fittings.

Miscellaneous Power Use

The larger refinery units use oil- or gas-fired furnaces to heat the feed stock; however, in the specialty products field, units and quantities are small and electric heating equipment is applied to certain of them, presenting another 440-volt load. Isolated locations where steam is not available may require the use of electric heat.

A great many refinery instruments are connected by means of tubing to the various pipes and vessels. It becomes necessary especially during cold weather to heat certain of these instrument lines to keep their contents fluid; this may be done by wrapping the interconnecting tubing with electric heater cable. The instruments themselves are similarly protected by heater cables where necessary.

Long pipe lines and particular operations sometimes require cathodic protection. In the case of pipe lines, power must be supplied to cathodic protection units at intervals along the lines which adds distribution difficulties. Cathodic protection of boiler-house equipment and condensers is of standardized type.

Summary

The use of electricity in refineries has increased tremendously in the last decade; this increase can be primarily traced to:

1. Development of equipment that is suitable for use in refinery atmospheres.
2. Development of improved mechanical equipment.
3. Development of generating equipment of industrial size having suitable operating economies.
4. General advance in the engineering arts.
5. Development of increasingly complex refinery processes.

Discussion

Everett E. Thomas (General Electric Company, Schenectady, N. Y.): Mr. Weeks and associates have prepared a timely paper for drawing attention of people in the electrical industry to requirements for the application of electrical power in oil refineries. They are to be congratulated for this work which should benefit all who are interested in refinery electrification.

Methods of finding and producing crude oil, as well as progress in processes for refining it into commercial products, have interested me during the past decade and my interest grows as I become better acquainted with the oil industry. My close contact with power-application problems in the crude-oil industry has given me considerable respect for explosive and hazardous conditions to be met by proper design and application of electrical equipment for safer operation in gaseous areas.

Up to about 15 years ago, some refineries installed standard open-type motors with control in gaseous areas by placing them in

an air-conditioned room and projecting the motor shafts through a fire wall to the driven units while most refineries used electricity only for lights and for power in nongaseous areas. This situation prevailed until the development of explosion-proof motors and associated equipment made it economical and advisable to electrify processing apparatus. Also, substitution of a few tube stills for many shell stills called for much more power and much less low-pressure process steam. These conditions gave a decided impetus to practically complete electrification in crude-oil refineries.

As early as 1918, the electrical manufacturers began to realize the need for motors for explosive conditions in various industrial plants and the Underwriters' Laboratories tested an especially built motor later to determine the construction features really needed to meet hazardous conditions. Some 50-horsepower and 75-horsepower wound-rotor fan-cooled motors involving explosion-proof features were built for Russian oil-field drilling rigs as early as 1922. Later, a line of fan-cooled explosion-proof squirrel-cage motors up to about 50 horsepower was available and, as experience and knowledge increased, the line was rapidly extended so that at the present time motors up to 400 horsepower with "label" and larger without "label" are available.

Mr. Weeks and associates have included a discussion of individual enclosed induction motors. Economical and physical limitations of the explosion-proof construction prevent its use at the present state of the art in motors which are comparatively large either because of high rating as in case of hot oil pumps or low speed as for compressor drives. Inert-gas-filled construction has greatly extended the field of application in hazardous areas and is believed to be an outstanding contribution of the electrical manufacturers to refinery electrification. About nine years ago, there were built some 100-horsepower low-speed synchronous motors of totally enclosed fan-cooled construction and filled with inert gas under slight pressure for operation in a gaseous location. These motors were mounted on the crank shafts of reciprocating compressors.

Recently, an installation for driving hot oil pumps has been made using 1,000-horsepower 3,000-rpm induction motors of inert-gas-filled design and employing built-in heat exchangers in which water is used for cooling the inert gas. In the larger sizes, this substitution of water cooling for fan cooling results in a smaller and less expensive motor and is comparable in size to open-type motors. For nonhazardous areas where enclosed motor construction is required, several of the surface-cooler motors in larger sizes have been installed using air instead of inert gas. As compared to enclosed ventilated synchronous or induction motors, this has advantages of eliminating air ducts and, also, eliminating problems of supplying quantities of clean air.

Dual drives imply use of motors and steam turbines of same capacity. One modification is to use a turbine of about half the capacity of the motor for starting "on stream" and for emergency service to prevent coking in case of electrical power outage.

The trend of underground-cable construction for distribution involves suitable duct ventilation not only for dissipation of heat but to prevent accumulation of refinery gases in the duct work.

The fact that about half of the refinery load requires motors large enough to warrant using 2,200-volt design has caused general adoption of 2,400-volt generation and distribution. Employment of 4,000-volt wye generation and transmission may be considered initially since distribution expense would undoubtedly be reduced for large blocks of power and the larger motors can still be designed for this voltage but only for use without "labels" at this time since the Underwriters' Laboratories feel that there are some questions to be settled which include corona effects. It may even be found uneconomical in the long run to distribute the increasingly large blocks of power at either 2,400 or 4,000 volts for a distance of more than a few thousand feet, in which case 6,900-, 11,500-, or 13,800-volt generation for distribution to transformer substations located near the various load centers would be the solution. It is desirable to restrict these higher voltages to nonhazardous areas.

Short-circuit rupturing capacity of all power-control devices should be checked against initial and ultimate requirements. System growth makes it imperative for the user to check suitability of these devices from time to time. Frequently, 2,200-volt control requires protection which may be provided by use of group feeder reactors. The 440-volt control should be checked for short-circuit capacity even though its feeders may have considerable impedance.

Use of the synchronizing bus scheme in power stations is an effective way to provide protection for circuit breakers by means of current-limiting reactors. From 10,000- to 15,000-kw in steam-turbine generation at 2,400 volts may be the limit without resort to some scheme of short-circuit-current limitation as otherwise the initial short-circuit-current inrush becomes too great for conservative application of commercial circuit breakers. This limit is modified by pump-back from synchronous motors. The same breakers can be used on larger systems of higher voltage because the initial current is reduced with the increase in voltage. This means that the one-second rating of the breaker, which is a measure of its thermal and/or mechanical strength, becomes the limiting feature rather than its rupturing capacity at lower voltages. Hence, proper choice of voltage is a matter for close scrutiny with respect to the short-circuit capacity of available control and its relation to the over-all economics of the distribution system, including possible future growth.

An important recent development is the use of silver-coated contacts on devices and bus joints to minimize the effects of oxidation. Oxides on copper contacts must be wiped off frequently to prevent overheating if these contacts are fully loaded. Silver contacts do not overheat for normal duty but usually require arcing tips to prevent burning the silver.

Skimming or topping plants require about $1^1/_2$ horsepower-hours per barrel of crude oil and the cracking plant about 3 horsepower-hours. A complete refinery requires about $5^1/_2$ horsepower-hours per barrel of crude oil. There are about 460 active oil refineries in this country, and they represent throughput of 3,300,000 per day. Computations based upon these figures show approximate connected horsepower to be 1,800,000 and this includes 700,000 horsepower for electric motors. Evidently, there is much left to be done toward further electrification in crude-oil refineries.

G. R. Weeks, H. W. Giesecke, and C. M. Lathrop: Mr. Thomas' discussion is an interesting supplement to the paper. Alternate schemes for using dual-driven pumps have been presented; it should be made clear that considerations of economy and refinery setup determine whether the turbine unit of a dual-driven pump should have full or partial capacity. Dual drive is usually applied only to the largest or most important pumps of a unit. Unit charging pumps furnish the most conspicuous examples of dual drive. Small pumps are generally installed in duplicate with the spare unit arranged for steam drive. Where the unit is of large size and the refinery steam supply is ample, it is advisable in most cases to have full-capacity turbines for dual-driven machines in order to continue uninterrupted operation of the unit in case of electrical-power failure. Where the steam supply is limited or where the function or size of a unit is such that its shutdown in case of more than momentary power failure is not a serious matter, the selection of half-capacity turbines is warranted.

As to the choice of voltage for refinery distribution systems, it may be pointed out that an organization operating more than one refinery derives considerable benefit from selecting a voltage that can be commonly used by its refineries and that, at the same time, corresponds to general industrial practice; 2.4 kv is unrivalled in this respect.

Aside from designing for maximum safety, reliability of service must be considered above other factors in laying out an electrical system for a refinery.

It is felt that wye- or delta-connected rotating machinery is equally suitable for refinery use; however, there are reasons for recommending that systems operate ungrounded and that transformer banks consist of delta-connected single-phase units. The ability to operate on open delta up to the thermal capacity of the transformers is valuable in case one of a bank of transformers must be removed from service. Since a large margin of safety in insulation is usually built into refinery equipment and since the distribution voltages are comparatively low, the effect of abnormal voltage disturbances that may arise in ungrounded systems is considered to be slight. With an ungrounded system, operation of circuit breakers and shutdown of machines is avoided in most cases of momentary single-line faults due to lightning or accident.

The authors' experience covers one large refinery which uses 440- and 6,900-volt distribution. No difficulty has arisen here in obtaining motors of all required types and although 6,900-volt control equipment is somewhat special it is not comparably more expensive than 2,400-volt equipment. Such equipment consists of cubicle or panel and frame mounting of oil circuit breakers and accessory equipment. Where distribution at higher voltage is required the use of transformer substations, as Mr. Thomas suggests, is unquestionably indicated.

High-Capacity "Hydro-Blast" Circuit Breaker for Central-Station Service

W. F. SKEATS
MEMBER AIEE

W. R. SAYLOR
ASSOCIATE AIEE

Synopsis: The increasing demand for oilless circuit breakers has resulted in a number of contributions in that field. Outstanding among these from the standpoint of interrupting capacity at generator voltages is the "hydro-blast" circuit breaker, which has been developed in ratings up to 1,500,000 kva. This breaker has the feature of complete interchangeability with the standard *H*-type oil circuit breaker and thus combines all of the well-known advantages of that type with the total absence of inflammable material. This paper describes in detail the construction and operation of the 500,000-kva hydro-blast circuit breaker for central-station service, several of which have been in service for over half a year.

WHILE the oil circuit breaker has for many years given a very good account of itself in the United States, there has nevertheless been a gradually increasing interest in the elimination of inflammable liquids from circuit breakers as well as from other electrical apparatus. While not ordinarily thought of as a good insulator, water has a much higher dielectric strength for short periods than is commonly appreciated, and could therefore be expected to be effective in interrupting an arc. From the standpoints of noninflammability and availability, of course, it is very attractive. An investigation was therefore inaugurated some time ago looking toward the development of a practical breaker using water as the interrupting medium.

Two requirements of primary importance in such a device are that the water should not be subject to continuous dielectric stress in either the closed or the open position of the breaker and that all parts coming into direct contact with the water be carefully selected in order to eliminate corrosion in connection with these parts. These requirements are admirably satisfied in what has been known for many years as the *H*-type breaker in which each of two breaks per phase takes place in a small separate tank, to which the liquid is confined. The major insulation is air and the corrosion problem is simplified by the fact that all major moving parts, except for a part of the contact rods themselves, are outside of the pots and thus kept away from the water.

Principles of Operation

Early tests were therefore made on this type of breaker, supplied with cross-blast baffles of substantially the same construction as that used with oil. These baffles have been previously described in the literature, but a brief explanation of their action will be repeated here. Figure 1*a* shows schematically two cross-sectional views, taken at right angles, of a part of a pot using one of these baffles as applied in the oil circuit breaker and with the contacts in the closed position. The interrupting process is started by raising of the contact rod (3). This draws an arc initially from the bottom of the contact rod to the arcing bell (2). As the rod continues to rise and is withdrawn into the central hole of the baffle (figure 1*b*) the metal gates (1) at the lower end of this hole close under the influence of their compression springs, blocking off any direct flow of liquid or gas up through this hole and dividing the arc into two portions in series, one below the baffle and one in its central hole. The arc below the baffle generates pressure which forces the liquid through the cross-blast passage (4), which is shown in figure 1*b*, as entering the baffle from the bottom at the right, then passing horizontally over to the left side of the baffle and finally leaving the baffle from the top on this side. The horizontal passage intersects the central hole of the baffle, so that the liquid forced through this passage by the pressure below the baffle crosses the path of the arc. In oil this had been found to be a very effective means of arc extinction.

Tests on such an arrangement with water as the interrupting medium indicated the scheme to be fundamentally sound, but brought out the fact that the pressure generated by a light-current arc of given length is considerably less in water than in oil, while at high currents the pressures in the two liquids tend to be of about the same magnitude. Thus with an arc of fixed length, the pressure was either too low to supply the necessary cross-blast velocity for interruption at light currents or excessive from the standpoint of material stress at

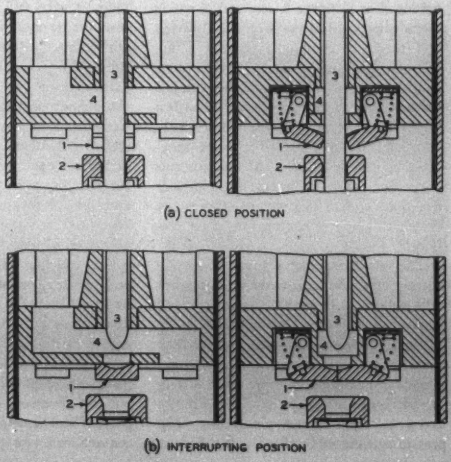

Figure 1. Type H oil-circuit-breaker cross-blast baffle and associated parts in cross section

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W. F. SKEATS is technical assistant to engineer and W. R. SAYLOR is application engineer, General Electric Company, Philadelphia, Pa.

The authors wish to express their appreciation of the co-operation furnished by many individuals, without which the success of this development would have been impossible. Within the General Electric Company, valuable suggestions have been contributed by members of the large-oil-circuit-breaker engineering section and by the staff of the short-circuit testing laboratory, while investigations in the Philadelphia works laboratory have contributed very largely to the choice of materials. The Philadelphia Electric Company is to be commended for its initiative in being the first to place breakers of this type in regular service on its system, thus providing the initial service experience.

Figure 2. Arc-control baffle

high currents. What was needed was a long pressure-generating arc at low currents and a short one at high currents.

This combination has been obtained without the addition of any moving parts by means of the arc-control baffle shown in figure 2. This baffle consists of a laminated iron core embedded in a disk of insulating material, which is shown as transparent in the photograph, but which is actually a hard rubber material that has been found suitable. It is located between the stationary contact and the cross-blast baffle in such a way that the arc is drawn through the central hole. Its action utilizes a modification of the well-known principle that an arc drawn in a slot of magnetic material is drawn magnetically toward the bottom of the slot. Now fundamentally, the "bottom" of the slot is that end at which the flux in question encounters the lower magnetic reluctance drop. Since iron has a saturating magnetic characteristic, it is obvious that a double-ended slot may be arranged as in figure 2, one end of which has a complete iron path of small section and therefore comparatively low reluctance at light currents and high reluctance at heavy currents, while the other end has an iron path of large section, but with a gap in it, so as to have a reluctance substantially independent of current magnitude. In this slot, light-current arcs are drawn to the end having the complete iron path, while heavy-current arcs are drawn to the end having the larger section.

This results in an arrangement whereby shortly after being drawn light-current arcs will tend to assume one path and heavy-current arcs a different path. If, then, the one path is made long and the other short, as indicated in figure 3, the object is achieved of providing a long pressure-generating arc for light currents and a short one for heavy currents. The pressure generated by this is now sufficient to bring about interruption at all values of current and excessive at none within a rating of 500,000 kva, which is equal to that of the corresponding oil circuit breakers. This results in a satisfactory interrupting performance throughout this

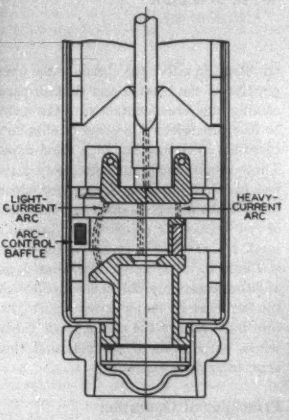

Figure 3. Diagram showing arc-control action

range. Figure 4 shows a photograph of a cutaway section of the interrupting element showing the actual configuration.

In order to remove all dielectric stress from the interior of the pot when the breaker is standing in the open position, a set of external disconnecting contacts has been provided as shown by figure 5 and figure 6. A wood crosshead is used which supports two segment-type contacts at each end. These segment-type contacts co-operate with bayonets which are mounted on cap insulators on top of the pots so as to make contact when the breaker is in the closed position and throughout the major part of the 20-inch stroke, but to leave a gap of about $2^1/_2$ inches above each pot when the breaker is in the open position. The path of current through the interrupting contacts of the breaker then runs from the bottom of one tank up through the contact rod to the two segment contacts which are connected in parallel at one end of the crosshead, thence to the bayonets mounted on the cap insulators, down these and across on the copper tie rods to the top of the cap insulators on the other pot of the same phase, then by a path similar to that followed on the first pot but reversed, to the bottom of this pot. The primary contacts make direct contact from pot to pot, shorting out the bayonets above the pots as well as the internal contacts.

The primary current-carrying contacts of the breaker are of the high-pressure line-contact type which combines the advantages of simplicity, effectiveness, and lightness of moving parts. The 600- and 1,200-ampere breakers use the butt type of contact in figure 5. The ratings of 2,000 amperes and above use double-finger wipe contacts which are also very compact as indicated by figure 7.

Adaptation to Field Service

The use of the arc-control baffle and series air disconnecting contacts described above resulted in the evolution of a hydro-blast breaker capable of supporting a 500,000-kva interrupting rating which is the same as that of the corresponding oil circuit breaker. With the use of the primary contacts, the current-carrying capacity is likewise brought into line. These changes had been made without increasing the space requirements of the breaker and in such a way as to permit modernization of the standard oil breaker in its original cell.

Figure 4. Cutaway section of interrupting element

From the point of view of adapting the breaker to the reliable service expected in field operation, the problems involved were mainly those of choice of material. It was obvious from the beginning that exclusive of the new features which made successful the utilization of water as an

interrupting medium, a number of changes would have to be introduced to cope with the altered chemical and physical picture presented inside the interrupting units. The comparable oil breaker had shown itself to be more than satisfactory over a period of many years' service as evidenced by the fact that over 30,000 of these breakers had been put into service throughout this period and operated successfully from the standpoint of both undiminished interrupting ability and unimpaired current-carrying qualities over long periods with very moderate maintenance. The goal set was a breaker using water as an interrupting medium that should be comparable not only in interrupting ability, weight, and cost, but also in sturdy and enduring construction to its proved counterpart in oil.

As a direct outgrowth of the type *H* oil circuit breaker, this breaker assembly includes a number of elements which have undergone only the changes necessary to accommodate them to immersion in water. The Herkolite and fiber parts as well as the plywood baffles and certain steel parts were immediately eliminated because of their deterioration when immersed in water. In their place, a synthetic material was found to be practical for the cylindrical spacers which hold the baffles in their proper locations; the bushing and the arc control baffle are molded of a hard substance which has shown the combination of long life and good mechanical and electrical properties, including ability to withstand the erosive effect of an arc; the tank lining is made of a material which adapts itself readily to the inside of the tank; the cross-blast baffle uses material which has ability to stand up under water and has shown itself to have excellent resistance to the arc. The metals to be used were chosen as a result of extensive steam and weathering tests on various combinations to determine which of them would produce a minimum of corrosion. This resulted in an assortment of metallic materials, including bronze, Elkonite, brass, stainless steel, and tin-dipped steel tank, that showed only slight tarnishing after prolonged exposure.

Water differs from oil in that its breakdown under the influence of the arc is a completely reversible process, leaving no permanent gases. This gave rise to the thought that a vent might be found unnecessary on these breakers and circuit interruption tests without a vent have shown this to be a fact. Thus the separating chambers and vent piping which are conventional on oil circuit breakers are entirely dispensed with.

With the elimination of the vent, the pot becomes practically a sealed chamber and the loss of water by evaporation may be expected to be very slight. Laboratory tests have shown this to be the case. In these tests, a tank was subjected to a heating cycle of 12 hours on and 12 hours off, resulting in temperature fluctuations from about 20 degrees centigrade to about 70 degrees centigrade. Under these severe conditions the loss by evaporation was at the rate of about $1^1/_2$ inches per year. Field experience, as might be expected, has shown an even lower loss. The circuit interruption tests listed in table I demonstrate that a water level variation of 3 inches may be allowed without any effect upon the breaker performance, so that a very reasonable maintenance schedule will be satisfactory from this standpoint.

Table I. Representative Arc Durations at Different Water Levels, 500,000-Kva Hydro-Blast Breaker

Single-Phase Tests at 14,500 Volts, 60 Cycles. Water Level Range—Three Inches

Maximum Water Level		Minimum Water Level	
Current (Amperes)	Arc Duration (Cycles)	Current (Amperes)	Arc Duration (Cycles)
1,200	2.1	1,200	1.5
2,100	1.2	2,900	1.1
4,300	1.5	4,900	1.3
6,200	1.3	6,900	1.3
9,900	1.6	10,000	1.1
12,900	1.4	13,000	1.3
14,300	1.3	20,000	1.2
17,800	1.1	20,500	1.2
19,600	1.3	21,000	1.0
20,000	1.0	24,000	1.0
26,000	1.3		

Tests

The breaker has, of course, been subjected to exhaustive tests. Table I,

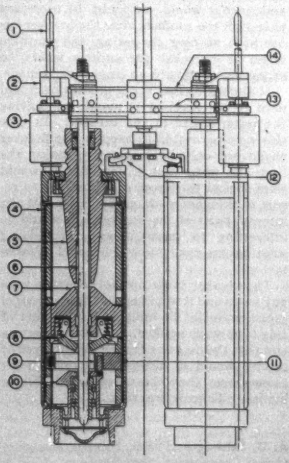

Figure 5. Hydro-blast circuit breaker, 500,000-kva rating

1—Bayonet
2—Segment-type contact
3—Cap insulator
4—Tank lining
5—Bushing insulator
6—Contact rod
7—Cross-blast baffle
8—Gates
9—High-current runner
10—Low-current runner
11—Arc-control baffle
12—Primary contacts
13—Copper tie rods
14—Wood crosshead

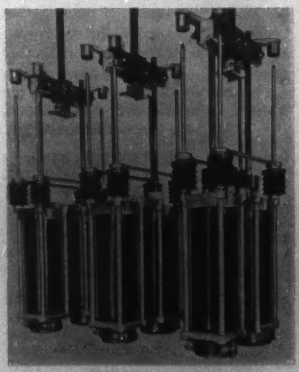

Figure 6. Hydro-blast circuit breaker, 500,000-kva rating, in open position

Figure 7. Double-finger wipe contacts

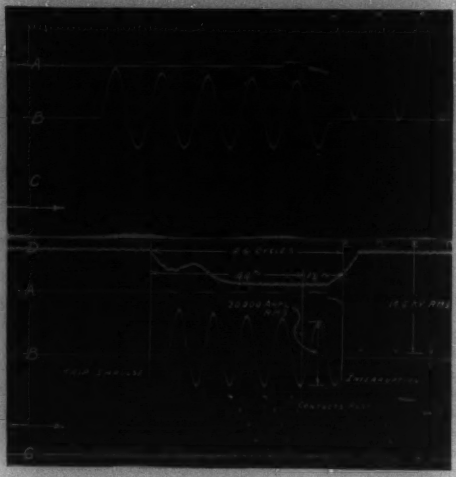

Figure 8. Typical interruption at breaker rating

A—Arc voltage
B—Current
C—Pressure below baffle

A—Arc voltage
B—Current
C—Contact travel—one-half inch per step
D—Trip-coil current

which has already been referred to, shows excellent performance on single-phase tests under the severe conditions of 14,500 volts impressed across a single pole. Table II shows similar data from three-phase tests. Both of these tables show interruption of currents exceeding that corresponding to the 500,000-kva rating of the breaker. Figure 8 shows an oscillogram of a typical interruption approximately at the breaker rating. The arc duration was limited to 1.2 cycles and the over-all time from trip impulse to interruption was 5.6 cycles. The performance is thus substantially the same as that of the corresponding oil circuit breaker.

Field Experience

Six oil circuit breakers which had been in service for some years have been changed over to hydro-blast breakers of the 500,000-kva rating and been in service in this form since the early fall of 1938. During this time as many as three short circuits have been interrupted by a single breaker. All short circuits have been interrupted promptly and expeditiously and the performance has been satisfactory in all respects, the only damage being a very slight burning of the contacts, which is to be expected.

Higher Interrupting Ratings

This paper has been primarily concerned with the 500,000-kva rating of the hydro-blast breaker, which has advanced somewhat farther than the other ratings. Work has progressed far with the development of both the 1,000,000-kva and the 1,500,000-kva ratings, however. Satisfactory circuit interruption tests have been made on a development sample of the 1,500,000-kva rating at current values extending up to 60,000 amperes.

Conclusions

The hydro-blast breaker, using a non-inflammable interrupting medium, has been developed in ratings from 500,000 kva to 1,500,000 kva at 15,000 volts. This breaker may be regarded as the latest stage in the development of a circuit breaker which has enjoyed continuous high popularity, as the incorporation of one improvement after another has kept it well abreast of the art. The hydro-blast breaker has the same over-all dimensions as the oil circuit breaker of which it is an outgrowth, substantially the same general arrangement, and the same performance characteristics, except that the presence of inflammable liquid has been entirely eliminated. The various interrupting problems introduced by the change from oil to water have been overcome, and six months' field experience has confirmed the practicability of the arrangement.

Table II. Representative Arc Durations, 500,000-Kva Hydro-Blast Breaker

Three-Phase Tests at 14,500 Volts, 60 Cycles

Current (Amperes)	Arc Duration (Cycles)	Current (Amperes)	Arc Duration (Cycles)
1,180	1.7	16,000	1.4
1,320	1.9	15,000	1.5
1,320	1.9	17,000	1.5
4,500	1.7	18,000	1.4
4,000	1.6	16,000	1.6
4,800	1.7	15,800	1.6
6,800	1.7	23,000	1.7
6,600	1.9	22,000	1.8
7,100	1.9	22,000	1.8
9,500	1.5	27,000	1.7
9,500	1.7	30,000	1.4
10,300	1.7	20,000	1.7

Discussion

J. A. Elzi (The Commonwealth & Southern Corporation, Jackson, Mich.): Developments in circuit breakers utilizing non-inflammable material in place of oil as the arc-extinguishing medium are of considerable importance and the results obtainable by using water for this purpose, as described in this paper, are highly interesting. The oscillograms and test results given seem to indicate that in general the performance of this breaker is quite comparable to that of an oil circuit breaker.

As the authors have mentioned, water is readily available, but presumably the water used in the breaker would have to meet certain requirements as to purity to avoid corrosion within the breaker and to maintain its arc-interrupting ability. It would seem that even a very small percentage of impurity in the water might be detrimental and since it would, no doubt, be necessary to inspect the contacts after the breaker has operated at near its rating, the question arises as to what precautions would be necessary when such an inspection is made.

It also seems that every precaution would need to be exercised to avoid ever having the water freeze in the breaker. In case this were permitted to happen, the breaker would not only be inoperative during the time the water was frozen, but it would seem logical to expect such freezing to result in permanent damage to some of the internal parts of the breaker. It would be interesting to know if any antifreezing solutions are available which would be satisfactory.

The breaker tanks are not provided with any vents and it would appear that excessive pressures might be built up if a breaker of this type were applied on reclosing service and that the derating factors for this type of service would of necessity be quite a bit more severe than those now applicable to modern oil circuit breakers.

A. C. Schwager (Pacific Electric Manufacturing Corporation, San Francisco, Calif.): The authors have to be commended for the ease with which they have been able to transform one of the most popular oil circuit breakers into one in which the hazard of an inflammable liquid is eliminated.

On a recent study trip in Europe, I had the opportunity of examining various water circuit breakers, but in spite of the several years of development, breakers of 1,500,000 kva, as described by the authors, were not available. In Europe the water circuit breaker has not been entirely satisfactory and just recently its manufacture has been

abandoned by at least two large manufacturers. In some breakers installed it was found advisable to change the interrupting liquid back to oil, in order to obtain more satisfactory operation. In view of these facts, one can more fully appreciate the difficulties which the authors have had to overcome in developing the breaker described.

In connection with the design proper I would like to ask a few questions:

(1). In closing in slowly on a short circuit, an arc is formed and steam is generated prior to the time the contacts touch. This high-pressure steam can exert a considerable force upon the moving contact, retard and possibly prevent the closing. I wonder if this phenomenon has been observed, and if so how its effect was overcome.

(2). Although water eliminates the danger of fire hazards, European practice, using Herkolite and fiber parts within the chamber, has shown that a sustained arc can produce a sufficient amount of gas completely to smoke out a station. It would be interesting to know if this shortcoming has been eliminated in the materials developed by the authors, particularly if the gases are of nonpoisonous nature.

(3). I am sure that this new development has thrown considerable light upon the theoretically involved problem of arc interruption. The authors refer to the high dielectric short-time strength of water; the question therefore arises whether this factor alone is sufficient to explain the performance. Several cycles elapse from the time the arc is interrupted to the instant the series air gaps open. Is the insulating ability of the breaker during this relatively long time interval due to a layer of water interposed between the contacts or due to the presence of steam?

B. P. Baker (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The reaction to the unique development described in the paper by Messrs. Skeats and Saylor will be most interesting to those concerned with the trend in American switchgear development.

I concur with these gentlemen in their belief that "the oil circuit breaker has for many years given a very good account of itself in the United States."

For some years we have recognized that there are rather special applications where the duty and frequency of operation are extremely severe. In these cases the complete elimination of oil, accessibility of contacts, and reduced maintenance requirements have justified our offering a line of oilless circuit breakers up to approximately 800,000 kva at 15 kv.

As early as 1922 we became interested in water as an interrupting medium, and even went so far as to acquire rights under the Nicholson patents. For a good many years now we have watched the work of a large European company on the "expansion" breaker, which was the first commercial form of water breaker. We have bought and tested various types of these breakers for both high and low voltages, and have obtained considerable information about their performance. Up to the present time however, our conclusion has been that the water breaker is not as well suited to American requirements as the De-ion type of air breaker.

We note that Messrs. Skeats and Saylor have carried their interrupting tests on a development sample of the 1,500,000-kva rating to 60,000 amperes. In view of the rather high power represented by such laboratory tests, it would be interesting to know at what voltage they were made and whether any special test connections were used.

The authors seemed to have investigated thoroughly the suitability of materials for operation in water and have reported on their adaptability from the corrosion point of view. Their conclusions generally confirm the results obtained by us. While the effect of the water on certain materials may not be serious, I do not believe that we can safely conclude that the effect of the various materials on the water can be taken too lightly. It would, therefore, be of interest to know the kind of water used, the upper limit of conductivity, and how this is affected by time and interrupting duty.

In this interrupter the old problem of volts interrupted per inch of arc as an inverse function of current reappears. Here again a rather ingenious solution has been offered by moving the arc from its point of inception, in one direction to lengthen it for low currents and in the opposite direction to shorten it for high currents. It seems rather unfortunate that at high current it is necessary to draw a long arc and then deliberately move it from its point of inception in order to shorten it, thus consuming unnecessary time, producing extra burning, arc energy, and pressure.

The author points out that in contrast to an oil breaker the water-breaker "pot becomes practically a sealed chamber", and at another place "pressure generated by a light-current arc of given length is considerably less in water than in oil, while at high currents the pressures in the two liquids tend to be of about the same magnitude". How these two conditions can exist needs explanation. Our experience indicates that the total volumes of gas generated are approximately the same for oil and for water but that a larger part of the gases formed by the arc in water rapidly recombine or condense leaving a smaller volume of permanent gases. At high currents the rate of generation is so high that condensation during that time is almost negligible and the pressures produced are about the same as for oil. However, at low currents the condensation of the steam is not negligible and the pressures generated are less than those when oil is used. This relatively faster condensation may be caused not only by the smaller rate of gas generation but also by the smaller bubbles which have walls closer to the arc and which have a relatively larger surface area in proportion to the volume of the bubble.

I was surprised to find that the average speed of the contacts from the point of separation to arc extinction is approximately 25 feet per second and I am wondering if I have interpreted the oscillogram correctly. With two series breaks per pole the arc is lengthened at the rate of approximately 50 feet per second. I had never regarded the *H* breaker as having such tremendous acceleration and wonder if there is anything inherent in this type of water breaker which requires such speed. Since the moving parts include the main contacts as well as the auxiliaries, I would be interested in knowing what special means have been required to get the acceleration and shock-absorbing effect.

D. C. Prince (General Electric Company, Philadelphia, Pa.): For many years there has been a search for some liquid which could be used in place of oil in a circuit breaker. The ideal liquid would possess such properties of transil oil as dielectric strength, especially under arcing, and, at the same time, be noninflammable. It should, of course, have other properties, such as constant viscosity, stability, low volatility, be noncorrosive, and have low cost, to mention only a few of the requirements.

For several years we have made a practice of trying out as a circuit-breaker fluid any liquid that anybody cared to mention, which offered any hope of success. Of all the liquids tried, water alone has seemed to offer any possibility of being useful in a commercial design.

Now that a water breaker has been produced which meets the exacting requirements of the high-power test station, and which makes possible an oilless circuit breaker up to the highest commercial ratings for station service, the next step is to see how such a design will meet the requirements of day-to-day operation in the field.

W. F. Skeats and W. R. Saylor: Mr. Elzi and Mr. Baker have asked about the purity and other characteristics of the water. The water used in the majority of tests on the hydro-blast breaker is Schenectady tap water. A typical series of about ten interruptions at moderate and high currents has been shown to reduce the resistivity of this water about 50 per cent with no accompanying deterioration in performance of the breaker. Inasmuch as the resistivity of the water has been quite low in all tests, it seems obvious that the presence of minute amounts of impurities such as might be picked up from the metals or insulating parts of the breaker would have no deleterious effect, and the successful field experience, of almost a year, as well as the many interrupting-capacity tests seems to bear this out. In view of the wide variations in tap water throughout the country, however, distilled water is recommended for general use.

It is not necessary to inspect the contacts of the water circuit breaker any more frequently than those of the corresponding oil circuit breaker, and the necessary precautions at the time of inspection are no more stringent than in the case of the oil circuit breaker.

Since these are indoor breakers, it is not felt that the requirement that the water should not freeze is at all embarrassing. However, antifreeze has been in use in this connection in Germany for a number of years.

The pressures obtained in the air space of the breaker are but a small fraction of those below the baffle and of that which the structure will stand, so that the absence of vents will not affect the derating factor on reclosing service.

The problem of circuit closing has been

met by a modification of the disconnecting contacts causing them to close after the interrupting contacts, and an arrangement has been developed which has been found satisfactory at the highest currents.

In order to determine the nature and extent of disturbance upon failure, this breaker has been opened under a short circuit of rated interrupting capacity without water in the tanks. After a few cycles of arcing inside the tanks, the arc was transferred outside the tanks, generating no more smoke than any other arc in air. Furthermore, with the cubicle arrangement now used with these breakers, such smoke as is generated should be largely confined to its own cell. The gases are not poisonous.

Unfortunately the development throws no light on the mechanism of arc interruption in the way that Mr. Schwager anticipates. The disagreement in this field centers upon the first millisecond or less after current cessation. Beyond this time there will be little disagreement that there will be sufficient dielectric between the contacts of such a breaker as this to render the voltage gradient across it comparatively low.

With reference to Mr. Baker's question, no special test connections were used, the breaker being tested up to the capacity of the testing plant at 14,500 volts, 8,400 volts, and 4,200 volts. The 60,000-ampere tests were obtained at 4,200 volts across a single-pole unit, but with only one breaker tank per pole instead of two. With this breaker these should be the equivalent of tests at about 8,000 volts, which is very nearly equal to leg voltage at 15 kv.

It is considered very unlikely that a long arc ever exists at the pressure-generating gap under high-current conditions. The metal piece which forms the lower terminal of the high-current arc as shown in figure 3 of the paper is fairly close to the contact rod when the latter extends through the arc-control baffle, and with the normal rapid expansion of the high-current gas bubble and the magnetic effect of the arc-control baffle combined, it is believed that the arc will strike from the contact rod to this metal piece while their separation is still quite short.

The explanation which Mr. Baker offers for the difference of the pressure characteristic of water from that of oil is very interesting and parallels closely one which has been suggested by the authors' associates. Another contributing factor may lie in the fact that oil is a mixture while water is substantially a single substance. Thus the more volatile constituents of the oil in the neighborhood of the arc may be vaporized rather readily by a light current, so that more gas in proportion would be generated in oil by a light current than by a heavy current. Since no such effect occurs in the case of water, a difference in the pressure characteristics similar to that which has been observed may be expected.

This breaker uses no special means for acceleration and shock absorption other than those standard on the *H* circuit breaker.

The question of the future of this type of breaker is one which only time can answer. The authors have been aware, of course, of the recent European history of this type of breaker and have had available complete design data on the water breakers manufactured by one of the European companies. They have made tests embodying these ideas and, as Mr. Baker has done, found them not very well suited to American practice. They believe, however, on the basis of both laboratory tests and field experience that the present breaker has overcome all serious shortcomings. Therefore, since this breaker exceeds by almost two to one the interrupting capacity of any earlier oilless breaker in its voltage range, it seems to be indicated that until other oilless breakers show a much greater advance than in the past few years, the hydro-blast circuit breaker will enjoy a good field of application.

The Anomalous Behavior of the Moving Systems of Single-Phase A-C Watt-Hour Meters at No Load

F. C. HOLTZ
MEMBER AIEE

Synopsis: Investigation reveals the moving systems of induction watt-hour meters to be in a peculiar state of motion under the condition of potential excitation only. The present paper offers a simple explanation for its origin and provides a method for recording and determining the actual value of the motion in various parts of the moving system. Interesting conclusions may be drawn from the investigation which throw much light on the problem of meter-bearing performance.

IT IS generally known among electric metermen that the moving systems of a-c watt-hour meters under the condition of no load with potential element excited are in a peculiar state of vibration. This phenomenon frequently exhibits itself as a rattle or vibration of the upper pivot if unoiled and is easily felt by slightly touching the edge of the disk with one's finger.

The writer, when discussing this matter with George F. Shotter of London, England, was advised that under suitable illumination and with sufficient magnification the actual motion of the peripheral edge of the disk had been observed as a figure eight, characteristic of Lissajous' curves. This discussion led the writer to investigate the phenomenon and develop methods for more accurately observing and recording the motion. Such motion can also be predicated on theoretical grounds as illustrated by the following considerations which are sufficiently accurate to explain the observations and predict the general nature of the motion. The total labor may be considerably reduced by making some very obvious assumptions as follows:

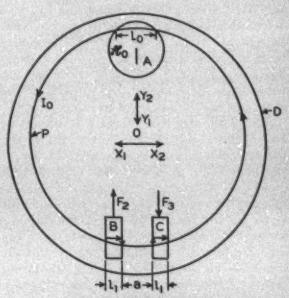

Figure 1. Elementary diagram of disk and interacting elements

1. The distribution of the driving and damping fluxes associated with the meter disk are generally symmetrical with respect to a plane perpendicular to and passing through its center.

2. The movement being very small and the upper pivot being at a considerable distance from the disk, it is assumed that the motion is parallel to the plane of the disk and that the motion of the lower pivot is substantially that of the center of the disk.

3. The total eddy-current distribution in the disk which causes the motion may be replaced by an "equivalent" filament of current interacting with the field of the permanent magnets and the a-c potential-element field.

4. The impedance of the path through

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F. C. HOLTZ is vice-president and chief engineer of the Sangamo Electric Company, Springfield, Ill.

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which the filament of eddy current circulates is wholly resistance.

5. The permanent-magnet damping fields are of equal but opposite strength and symmetrically placed with respect to the plane referred to above.

With these assumptions we may proceed with the equations of motion in the steady state in which,

$\mathfrak{C}_0$ = maximum value of the assumed uniformly distributed field strength as shown in figure 1
f = frequency
$\omega = 2\pi f$
I_0 = maximum value of the "equivalent" eddy current in the disk
l_0 = length of the eddy-current path in the a-c field
l_1 = length of the eddy-current path under each of the permanent magnets
H = intensity of the permanent-magnet field in the disk at the points associated with the eddy current
$\mathfrak{C} = \mathfrak{C}_0 \sin \omega t$ = instantaneous value of the a-c field strength. If i is the instantaneous value of the eddy current in the disk we have, in view of (4)
$i = I_0 \cos \omega t$

Referring now to figure 1, let P denote the filament or equivalent eddy current

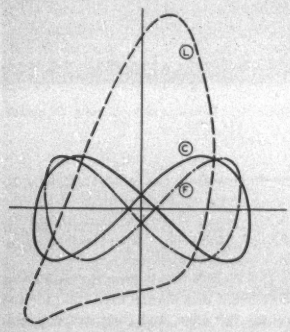

Figure 2. Motions derived from simple theory

in the meter disk, D and A, B and C, the respective locations of the a-c and d-c fields.

The force caused by the interaction of the a-c field and the equivalent eddy-current filament is

$$F_1 = l_0 \mathfrak{C}_1 = \mathfrak{C}_0 l_0 I_0 \sin \omega t \cdot \cos \omega t = K \sin 2\omega t$$

where K is a constant. It is therefore seen to be a double-frequency quantity and with the usual assumptions as to symmetry and direction of field is directed through the center of the disk along the line Y_1Y_2.

We may also assume that this produces a harmonic motion of the disk in the same direction but in view of its inertia, and other factors, the motion is not quite in phase with the force but differs therefrom by a small angle α.

With these assumptions the component of motion of the center of the disk arising from the interaction of the eddy currents and a-c field is of the form $y = K_1 \sin (2\omega t + \alpha)$. The disk, as a whole, will also be moving in the same manner.

The same eddy current will also interact with the field of the permanent magnets B and C. The filament of eddy current under each magnet may be resolved into two components which are parallel and perpendicular respectively to the direction Y_1Y_2. As may be seen in the figure, the components parallel to the Y_1Y_2 direction are relatively small and may therefore be ignored in the present analysis. It is interesting, however, to observe that since these components in respect to each magnet are relatively reversed and the magnetic field is also reversed the effect is to produce an oscillation of the disk about its center. The components of the eddy current under the magnets and perpendicular to the line Y_1Y_2 interact with the field, H, to produce forces in the disk parallel to this direction.

Under the magnet B there exists a force

$$F_2 = H l_1 I_0 \cos \omega t$$

And under C a force

$$F_3 = -H l_1 I_0 \cos \omega t$$

It is apparent that these two forces combine as a couple of moment

$$M = F_2 (a + l_1) = (a + l_1) \cdot H l_1 I_0 \cos \omega t$$

Since the observed motions are of extremely small magnitude we may assume that this moment gives rise to a component of motion of the center of the disk along the direction X_1X_2 of magnitude

$$X = K_2 \cos (\omega t + \alpha_2)$$

Where K_2 is a constant for any given set of conditions.

It is to be noted that this motion is harmonic and of the same frequency as the supply. By suitably readjusting the value of α, we may rewrite the equation of motion of the center of the disk in parametric form.

$$y = K_1 \cos (2\omega t + \alpha_1)$$

$$x = K_2 \cos (\omega t + \alpha_2)$$

Since y goes through its period twice as fast as x the curve in general consists of two loops. These curves are, in fact, the typical Lissajous' curves.

In view of the numerous factors which present themselves in attempting a general solution of the disk motion, it cannot be argued that the simple equations above adequately represent all actual possible motions of the system. Some difficulty would, for example, be encountered in even the more simple case of evaluating the inertia, damping coefficients, and other restraining forces under the action of the single force in order to arrive at the equations of motion. They do, however, give a very close approximation by assigning various constants in the equations of motion.

In precisely the same way it is possible to establish the corresponding motion of other portions of the disk. This has been done and by appropriate choice of constants, and transformation equations the relative motions have been plotted in figure 2 in which C represents the motion of the center of the disk; L, the left peripheral edge, and F, the front peripheral edge between the magnets. In this sense the constants were merely varied until the curves corresponded with the observed values rather than using the equations to predict the actual observed motion. It will be seen that these curves do represent with considerable accuracy the nature of the observed motion and therefore the

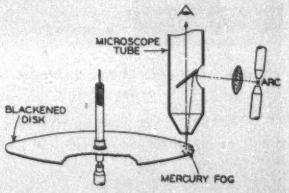

Figure 3. Setup for observing motion at edge of disk

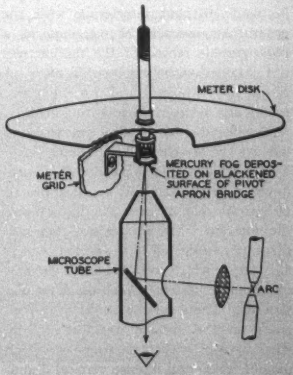

Figure 4. Setup for observing motion at center of disk

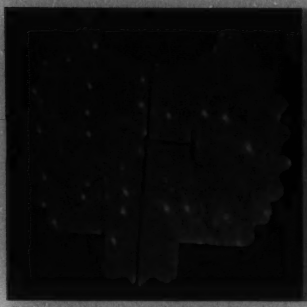

Figure 5. Center of disk, no excitation

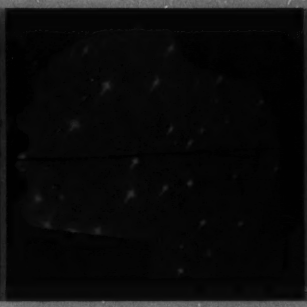

Figure 6. Left edge of disk, no excitation

Figure 7. Center of disk, 115 volts, 60 cycles

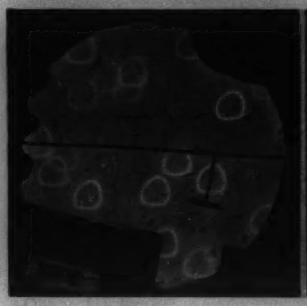

Figure 8. Left edge of disk, 115 volts, 60 cycles

Figure 9. Front edge of disk, 115 volts, 60 cycles

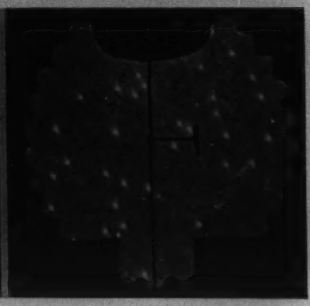

Figure 10. Center of disk, 90 volts, 60 cycles

simple assumptions are sufficient to predict its origin.

Experimental Procedure

Since the magnitude of motion was extremely small and the observations had to be made without interfering with the general arrangement of meter parts, a photographic record of the motion was not obtained without some difficulty. A simple and also beautiful procedure was finally arrived at in the following manner.

The disk was first given a heavy coat of lacquer heavily charged with lamp black. This, on drying, gave a surface which produced no reflection and hence appeared uniformly black even under intense illumination. The surface was then momentarily subjected to the action of mercury vapor which collected small globules of the order of 0.0001-inch diameter and smaller. These small globules would remain on the surface undisturbed and when viewed with a microscope of high magnification and intense vertical illumination the appearance was that of a star image of unusual brightness and small size. When the disk was in motion each tiny spot, due to persistence of vision, produced a true figure of the motion which could be measured and photographed. The general arrangement of apparatus is shown in figure 3.

In order to observe and record the motion of the center of the disk, the arrangement shown in figure 4 was used. In this case the jewel screw was replaced by a small bracket secured to the meter grid and on this was mounted the jewel which supported the meter pivot and moving system. By cutting away the dust cap surrounding the pivot until it resembled an inverted U it was possible to bridge this with a small strip on which the mercury globules had been deposited. The microscope in an inverted position gave the desired view.

Figures 5 and 6 are photographs showing the appearance of the illuminated points at the center and left edge respectively for the condition of no current and no potential excitation. In these as well as subsequent photographs the magnification was 500 diameters. Since there was some possibility that the motions might be influenced by the location of the anti-creep slots, these were marked on the negative by a short bar connected to the center of the disk. No appreciable influence was however observed.

Figures 7, 8, and 9, show the motion for no current and normal excitation for the center, left edge, and front, respectively. The close similarity between these three photographs and those shown in figure 2 is to be noted, indicating that the simple assumptions made at the beginning are sufficient to account for the observed motion. As is to be expected, a reduction in voltage should give a corresponding reduction in the motion. This is shown in figures 10, 11, and 12, showing the motion at the center, left, and front edge respectively when the voltage is reduced from 120 to 90 volts. On account of the friction offered by the pivot, there is a point where the motion ceases at the center and becomes purely one of rotation. The above figures illustrate this. In a like manner increasing the voltage makes the effect more pronounced as is shown in figure 13, which illustrates the motion of the pivot at 135 volts.

Removing the permanent magnets has the effect of wiping out the single-frequency motion as is shown in figures 14 and 15 representing the condition at 170 volts, 60 cycles. Under these conditions reducing the voltage to 115 volts had the effect of completely arresting the motion as shown in figures 16, 17, and 18, illustrating the center, left, and front edge respectively. This condition is brought about by the fact that the pivot friction was sufficient to prevent motion, yet in the earlier photographs where higher forces caused the pivot to move, the double-frequency forces were able to act while the pivot was in motion.

Removing one of the magnets caused a pronounced change in motion as can be determined from the equations. In this case the motion is almost entirely in a radial direction across the remaining magnet. Figures 19 and 20 show the motion at the center and left edge respectively. Many other interesting effects can be pro-

Figure 11. Left edge of disk, 90 volts, 60 cycles

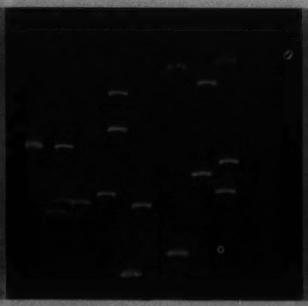

Figure 12. Front edge of disk, 90 volts, 60 cycles

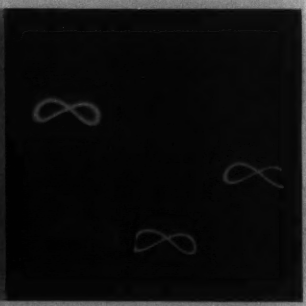

Figure 13. Center of disk, 135 volts, 60 cycles

Figure 14. Front edge of disk, magnets removed, 170 volts, 60 cycles

Figure 15. Left edge of disk, damping magnets removed, 170 volts, 60 cycles

Figure 16. Center of disk, damping magnets removed, 115 volts, 60 cycles

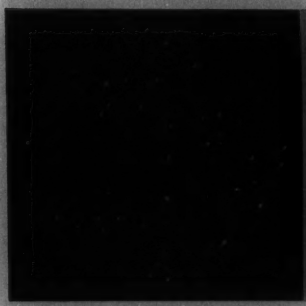

Figure 17. Left edge of disk, damping magnets removed, 115 volts, 60 cycles

Figure 18. Front edge of disk, damping magnets removed, 115 volts, 60 cycles

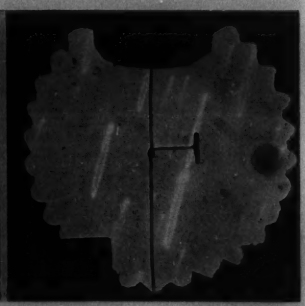

Figure 19. Center of disk, right-hand magnet removed, 115 volts, 60 cycles

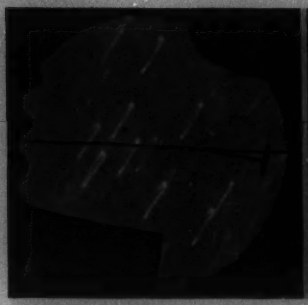

Figure 20. Left edge of disk, right-hand magnet removed; 115 volts, 60 cycles

Figure 21. Center of disk, 115 volts, 40 cycles

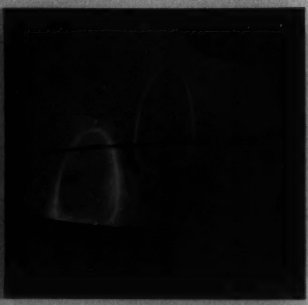

Figure 22. Left edge of disk, 115 volts, 40 cycles

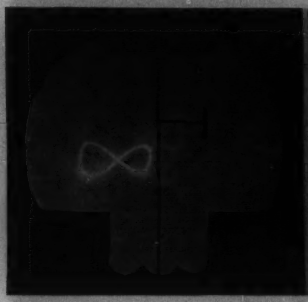

Figure 23. Front edge of disk, 115 volts, 40 cycles

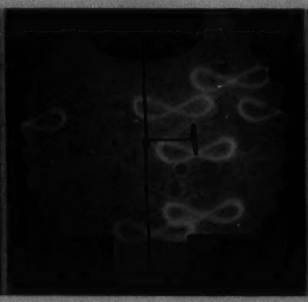

Figure 24. Ball-bearing construction, center of disk, 115 volts, 60 cycles

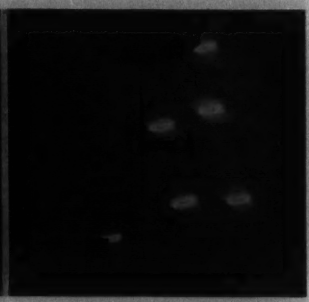

Figure 25. Ball-bearing construction, center of disk, 30 volts, 60 cycles

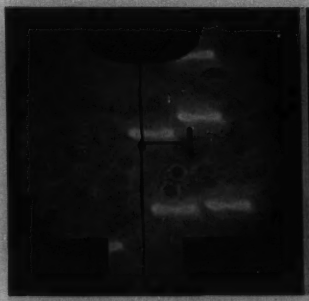

Figure 26. Ball-bearing construction, center of disk, 60 volts, 60 cycles

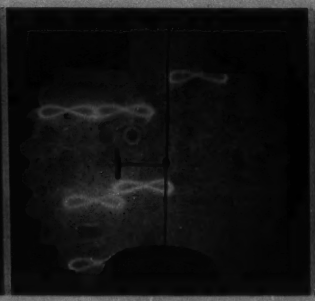

Figure 27. Ball-bearing construction, center of disk, 90 volts, 60 cycles

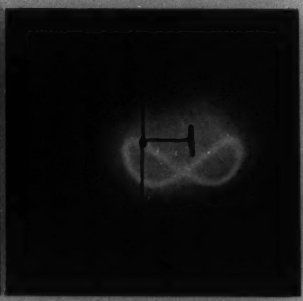

Figure 28. Ball-bearing construction, center of disk, 180 volts, 60 cycles

duced according to the variations made in the factors going into the constants of the equations. A reduction in frequency, for example, greatly amplified the figures as shown in figures 21, 22, and 23 showing the motion of the center, left, and front edge at normal voltage and 40 cycles.

Behavior of Moving System With Ball-Bearing Support

Because of the equally common use of the ball-type bearing, further tests were made to determine the relative motion of the disk under operating conditions similar to those applied to the meters with pivot-type bearing. In this type of bearing a $^1/_{16}$-inch ball moves between two sapphire cup jewels of approximately the same dimensions as those used with the pivot-type bearing. One jewel is carried by the meter spindle while the other is mounted in the lower jewel screw. In

order to draw conclusions as to the relative motion in both types of bearings under the stated condition, several photographs were made at the same voltage and frequency used in previous tests.

Figure 24 shows the motion of the center of the disk at 115 volts, 60 cycles. This should be compared with figure 7 which shows the motion of the center of the disk using a pivot-type bearing under similar conditions. It is to be noted that in this case the extent of oscillation is approximately double, indicating greater freedom of motion but not entirely so. The mechanical characteristics of the system are such as to permit a greater motion under the same forces.

In order to determine if the ball-bearing system exhibited lower friction and was therefore more responsive to the forces, photographs were taken at lower voltages as shown in figures 25, 26, and 27. It is to be noted that even at 30 volts some motion is recorded while at 90 volts it is very considerable. Figure 27 is to be compared with figure 10 which shows no appreciable motion under similar conditions. Figure 28 illustrates the motion at still higher voltages. In order to show the motion resulting from the double-frequency forces of the potential element only, the damping magnets were removed and photographs were taken at 180 volts, 60 cycles. This is clearly shown in figure 29.

It may be said that the motion of the disk when supported by a ball bearing is similar to that which takes place with a pivot bearing but of considerably greater magnitude.

Conclusions

Among the various conclusions to be drawn from the present study are the following:

1. The simple assumptions adequately explain the observed motion.

2. The motion can be reduced by (*a*) not having the electromagnet too near the edge of the disk, and (*b*) keeping the active area of the permanent magnets as near together as possible and of equal strength.

3. The motion of the meter pivot under no-load condition is in the form of a figure eight and the total travel as taken from the curves is approximately 0.002 inch per cycle or 0.12 inch per second. It is interesting to compare this amount of motion with the amount of motion which takes place between the pivot and jewel as a result of full load on the meter.

In this case the pivot moves up the side of the cup jewel until the forces are balanced by an amount such that the point of contact on the surface of the pivot is at a distance approximately

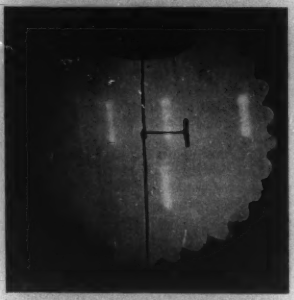

Figure 29. Ball-bearing construction, damping magnets removed; 180 volts, 60 cycles, center of disk

0.005 inch from the central axis.

Using a full-load speed of 0.4 revolutions per second, this results in a motion of 0.012 inch per second which is only of the order of one-tenth that referred to above. Since the pressure between pivot and jewel is approximately the same in both cases it may well be argued that the tendency toward wear of the pivot would be roughly ten times as much at no-load as under full-load operation and that the former takes place over an area of the jewel which is directly conducive to light-load inaccuracies. It must also be remembered that these same forces are active when the meter is under load and may therefore contribute to the wear.

An old assumption not wholly in accord with facts was that the amount of pivot wear was roughly proportional to the total number of meter-disk revolutions. The present investigation as applied to the pivot and cup type of bearing tends to indicate that the amount of wear is dependent upon the total number of hours during which the meter is standing idle with only potential applied, plus some function of the total number of revolutions. This might be expressed in the form of an equation as follows:

$$W = T + R + f(T,R)$$

where

W = wear
T = time in hours
R = total number of revolutions
$f(T,R)$ = some unknown function of both time and revolutions since these effects are not wholly independent

It must, however, be stated that the nature of meter-bearing wear is so complex and subject to so many unknown variables that it is quite unsafe to make any arbitrary assumptions except as we may ascertain new facts which would throw more light on the problem and explain a relatively large mass of observations.

It is, moreover, interesting to study briefly the behavior of the ball-type bearing under similar conditions of no-load operation. Since there exists no appreciable side thrust under the condition of no load, this bearing may be thought of as no more than a ball between two flat horizontal surfaces.

Under these conditions almost perfect rolling motion is secured with the result that there should be little or no wear. Since on appreciable load there is a combination of rolling and sliding, we may, as before, write the equation for wear as follows

$$W = R + f(R,T)$$

to indicate that the wear is almost wholly a function of disk revolutions and time, the latter being necessary to take care of such matters as corrosion, etc. Heretofore it has been the practice to lubricate pivot- and cup-type bearings while the ball bearings are not lubricated, although lately some manufacturers have recommended against oil in either type.

In this respect the conclusions to be drawn from the present investigation points clearly to the fact that without lubrication and under similar conditions any given alloy will perform better in a ball-type bearing than as a pivot type as related to watt-hour meters. This conclusion appears to be completely supported by experimental evidence.

Discussion

Otto A. Knopp (Pacific Gas and Electric Company, Emeryville, Calif.): To anyone interested in research work it is a delight to read the paper presented by F. C. Holtz and especially to people who are interested in watt-hour meters.

Watt-hour meters more or less as we know them today, have been operated for some 40 years with jewel bearings of conventional construction. Still we have learned very little of the behavior of the bearing so as to improve its performance.

Up until 15 years ago the watt-hour meter had many weaknesses and limitations so that the jewel bearing was considered on a par with, or better than, the other parts of the meter. Improvements in the design of the watt-hour meter during the last 15 years have removed many of its weaknesses and limitations, and the jewel bearing now stands out as the weakest member in its structural makeup.

A great many new designs for meter bearings have been proposed and perfected during the past several years, based, however, merely on service experience and limited tests and assumptions. Because of the lack of factual information, it is exceedingly difficult to decide which type of bearing will

be the best from the standpoint of long-life performance and cost.

Research work described in the paper presented by Mr. Holtz throws an entirely new light on the situation by bringing out the fact that the wear of the jewel bearing is greatest during the hours of no load on the meter. Wear on the jewel during no load hours is possible since it is a common practice to keep the meter that is in service excited with the line potential at all times.

This new and startling observation, the correctness of which has been proved so convincingly by Mr. Holtz, both by calculations and by ingenious experiments, will be of particular importance in giving a guide in the replacement of jewel bearings. It will, no doubt, also have an effect upon the design of the jewel bearings and possibly upon the design of the meter. Mr. Holtz's work represents an important scientific step in the exploration of the behavior of watt-hour meter jewel bearings, and it is hoped that more of this type of work will be done in the future until we have a clear conception of all the factors entering into the design of a satisfactory lower bearing for watt-hour meters.

There is one factor which may enter into this picture so as to reduce the excessive wear at no load. This reduction of wear may come about by a slight wearing of the jewel at the spot at which the pivot point rests during no load. The slightly increased friction may reduce this no load motion of the pivot to zero and when the load is placed on the meter, the pivot point, due to the side thrust, will be drawn away from the no load position and will slide or glide on a smooth, unworn part of the jewel cup. This side thrust, which is very large in the modern high-torque watt-hour meter, brings in new problems in the design of the bearing, and it is hoped that Mr. Holtz will continue his excellent work and thus give us more and more information of real value for the design, selection, and maintenance of the watt-hour meter jewel bearing.

J. H. Goss (General Electric Company, West Lynn, Mass.): The author points out that the phenomenon of vibration of an a-c watt-hour meter moving element under potential excitation alone has been generally recognized. The method of study of the vibration developed by the author is both novel and effective.

One effect of the vibration of the moving element is to reduce the friction in the register, top bearing, and bottom bearing. In fact the friction is reduced to the point that but a small fraction of the torque of the light-load compensating adjustment is required for it. The remainder is needed to correct the unbalance in the electromagnetic element and to compensate for the current iron permeability characteristic.

The equation of wear, $W=T+R+f(T,R)$, was set up for the pivot bearing. For a lubricated pivot bearing the wear of the pivot tends to reach a constant value as shown in a previous AIEE paper ("Lubrication Increases Life of Meter Bearings," T. A. Abbott and J. H. Goss, ELECTRICAL ENGINEERING (AIEE TRANSACTIONS), volume 54, April 1935, pages 428–31). This has been confirmed by actual tests both with watt-hour meters running under load and watt-hour meters operated with potential excitation only. The watt-hour meters operated with potential excitation only actually showed less wear by an appreciable amount than those operated under a moderate load.

The above equation would not represent the condition of wear of a well-lubricated pivot bearing, as neither the term T nor R is linear.

The author points out that in the case of the ball bearing with potential excitation only, a condition of true rolling exists. It is interesting to observe the motion of the ball in a watt-hour meter bearing under actual load conditions. This is possible if a microscope with a magnification of approximately 40 diameters is used. The ball spins erratically as the load changes and presents new points of contacts to the sapphire cups. This renews the actual bearing surfaces and coupled with the rolling action under condition of potential excitation only, no doubt accounts for the performance of the ball-type bearing operating without lubrication.

Paul MacGahan (Westinghouse Electric and Manufacturing Company, Newark, N. J.): This very timely paper by F. C. Holtz is of prime interest, both to the specialists in the field of metering and to the electrical industry in general.

The electrical industry depends entirely upon the registration of the meter for the wherewithal for its development—for its very existence, in fact. Thus, until a practical a-c meter was invented in 1888, the industry could not be financed to proceed beyond the narrow confines of the d-c system. Therefore, any factors contributing to the accuracy and permanence of the meters are of general interest to all concerned.

The reading of the paper discloses that the author is concerned with the vibratory motion of the moving element when excited by the simple single-phase magnetic field due to the voltage coil. This field induces corresponding secondary currents in the disk which do not produce rotation but only an oscillation due to harmonic attraction and repulsion.

Mr. Holtz has, in a very interesting manner, analyzed this condition by the aid of modern methods, both in theory and by laboratory. The conclusions are that the ball bearing should perform better than the pivot type in watt-hour meters.

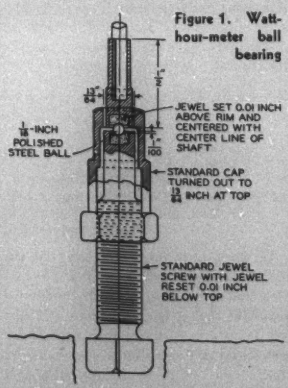
1/16-INCH POLISHED STEEL BALL
JEWEL SET 0.01 INCH ABOVE RIM AND CENTERED WITH CENTER LINE OF SHAFT
STANDARD CAP TURNED OUT TO 15/64 INCH AT TOP
STANDARD JEWEL SCREW WITH JEWEL RESET 0.01 INCH BELOW TOP

Figure 1. Watt-hour-meter ball bearing

Mr. Holtz correctly assumes that all meter engineers know the early history of this development. For the benefit of other engineers not intimately associated with the American meter art, it would seem desirable to add the following brief account of the early history.

The year 1897 brought forth the original so-called "round type" Westinghouse induction-type watt-hour meter. This meter was characterized by the use of a very light moving element and a high ratio of torque to weight, compared to earlier forms. It was small, and in many ways, a distinct advance in the art. The meter was designed by Doctor Frank Conrad and H. P. Davis.

The largest of the early utilities in the a-c field was the United Electric Light and Power Company of New York City, now a part of the Consolidated Edison Company. Mr. Davis' field investigations with W. E. McCoy of the United company led to a suggestion from Mr. McCoy that it would be desirable to use a readily replaceable pivot in the form of a small steel ball.

The year 1902 found the writer engaged as assistant to Frank Conrad in the design of watt-hour meters and instruments. At that time, we had just produced and put on the market an improved form of the original meter using a front-connected terminal chamber and improved means of adjustment.

The writer was directed to have experimental models designed and made, using ball bearings. Tests made by us brought out the fact that vibration in the moving element was causing the pivot bearings to wear rather fast. It took but the sense of touch and a magnifying glass to discover this vibration and to note that it existed even with only the voltage coil connected.

Figure 1 is a reproduction of a drawing based on the original freehand sketch, dated 1902, of the experimental ball bearing as finally decided on. This design comprised the use of a steel ball between two sapphire jewels. The idea was to avoid the wear of pivots because of vibration and rubbing friction, by substituting a rolling action.

The writer recollects considerable discussion on the question of whether the ball actually rolled or whether it only turned like a pivot. The claims that it rolled were questioned in a letter to the editor of *Electrical World*, by William Hallock (see page 700, *Electrical World*, October 21, 1905). To this, the writer replied, giving an explanation of the reason for the rolling action (see *Electrical World*, November 11, 1905, page 827).

It is interesting to note that today, 37 years later, the ball which is used is exactly the same as the one selected in 1902 as being the most suitable in size and quality for this purpose.

This ball bearing was introduced as a further improvement in the so-called sub *A* Davis-Conrad meter in the year 1902.

Another advantage soon became apparent, which was that this bearing did not need any lubrication whatever. In fact, it worked better dry than oiled.

While practically all the meters of the 1902 vintage have been replaced by modern types, many cases are on record of continu-

Transformation Theory of General Static Polyphase Networks

LOUIS A. PIPES
ASSOCIATE AIEE

Synopsis: Starting from the canonical equations of a general, linear, bilateral network and by the application of transformation matrices, giving the various current constraints in typical polyphase systems, equations are obtained which give the response of the most general wye-wye, delta-delta, and delta-wye static systems to arbitrary electromotive forces at the sending and receiving ends. Mutual inductances and capacitances are assumed between the various branches of the circuits.

The paper is concluded with a brief exposition of the method of symmetrical components from the transformation point of view and an application to the general wye-wye circuit is given as an example.

THERE has been considerable work recently in the application of tensors, dyadics, and matrices to electric circuit theory by Kron, Bewley, Sah, Reed, and others. The problem of general static polyphase systems in the steady and transient states does not seem to have been treated. It appears that the great power of these methods is nowhere more evident than when general systems are considered. Once having obtained the solution of these general systems, the solution of simpler ones come under special cases.

In the interest of such generalizations, and to illustrate the power and simplicity of matrix algebra in this class of problems, the study presented in this paper was undertaken.

The properties of matrices given in the paper "Matrices in Engineering" by Pipes[1] will be assumed in the following discussion.

Paper 39-117, recommended by the AIEE committee on basic sciences, and presented at the AIEE combined summer and Pacific Coast convention, San Francisco, Calif., June 26-30, 1939. Manuscript submitted August 23, 1938; made available for preprinting April 27, 1939.

LOUIS A. PIPES is faculty instructor in electrical engineering, Harvard University, Cambridge, Mass.

1. For all numbered references, see list at end of paper.

I. Notation

For simplicity, the following notation will be used:

Instantaneous values of currents and voltages will be denoted by small letters i_n, e_n, etc. Matrices whose elements are instantaneous values of currents and voltages will be denoted by $[i]$ and $[e]$ respectively.

Impedance operators of the form $z_{mn} = L_{mn}d/dt + R_{mn} + S_{mn}\int_{-\infty}^{t}()dt$ will be denoted by small z's, and matrices whose elements are impedance operators of the above form will be denoted by $[z]$.

Complex currents and voltages will be denoted by I_n and E_n respectively, and matrices whose elements are complex currents and voltages will be denoted by $[I]$ and $[E]$.

Complex impedance and admittance operators will be denoted by $Z_{mn} = jwL_{mn} + R_{mn} + S_{mn}/jw$ and Y_{mn} respectively. Matrices whose elements are complex impedance and admittance operators will be denoted by $[Z]$ and $[Y]$. This symbolism appears to be simple and convenient.

II. General Transformation Theory

Consider a general n-mesh circuit. Let the n mesh currents have the instantaneous values $(i_1, i_2, \ldots i_n)$ and let there be n voltages, $(e_1, e_2, \ldots e_n)$ acting on the contours of the n meshes. The canonical equations of such a general n mesh circuit may be written in the form:

$$[e] = [z][i] \tag{1}$$

where $[e]$ and $[i]$ are columnar matrices whose elements are the n mesh voltages and currents respectively and $[z]$ is a square matrix of the nth order whose elements are the various self- and mutual-impedance operators.

If we let ϕ_s be the total flux linkage with respect to mesh s due to all the self and mutual inductances on its contour, we have:

$$[\phi] = [L][i] \tag{2}$$

In this equation $[\phi]$ is a columnar matrix whose elements are the respective flux linkages of the n meshes and $[L]$ is a square matrix of the nth order whose elements are the self- and mutual-inductance coefficients of the circuit.

If T is the total instantaneous magnetic energy of the system, then:

$$T = [i]'[\phi]/2 \tag{3}$$

where $[i]'$ is the transpose of $[i]$.

Substituting the expression in (2) for $[\phi]$ into (3) we obtain:

$$T = \frac{[i]'[L][i]}{2} \tag{4}$$

If we let $(e_{c1} \ldots e_{cn})$ be the capacitance voltages induced on the conductors of the respective meshes, we have:

$$[e_c] = [S][q] \tag{5}$$

In this equation, $[S]$ is a square matrix of the nth order whose elements are the self- and mutual-elastance coefficients of the system. $[q]$ is a columnar matrix of the n mesh charges defined by:

$$[q] = \int_{-\infty}^{t} [i]dt \tag{6}$$

Now if V is the total instantaneous electrostatic energy of the system, we have:

$$V = \frac{[q]'[e_c]}{2} \tag{7}$$

where $[q]'$ is the transpose of $[q]$.

Substituting (5) into (7), we obtain:

$$V = \frac{[q]'[S][q]}{2} \tag{8}$$

ous operation of various ball bearing meters for 20 years or over without requiring any replacement of the bearings and without any lubrication problems.

F. C. Holtz: In replying to the remarks made by Mr. Goss, the author wishes to state that the equations of wear were, unfortunately, not a rigorous treatment of the subject. Both T and R should be some undetermined function of the time and revolutions respectively. In fact, even such representation may not be sufficient to explain a mass of observed data.

The part which vibration plays in reducing the friction of a meter register and other moving parts is most interesting and is probably responsible for the very uniform performance of watt-hour meters at light load. The presence of vibration was not recognized in some of the earlier forms of watt-hour meters; however, its advantages were appreciated and special devices were employed to produce sufficient vibration to maintain the moving system in a state of motion.

Mr. Knopp has pointed out in his remarks that a slight increase in friction may be sufficient completely to arrest the motion of the moving system. This has not been observed in lubricated pivot-type meters even after several years' operation; however, it is probably true that the motion was considerably reduced. It would be interesting to study the problem from this angle and determine under what conditions the motion could be arrested. Furthermore, as pointed out by Mr. Goss, certain advantages result from keeping the moving system in a state of vibration.

Letting the induced voltages due to the resistances on the various mesh contours of the system be $(e_{r1} \ldots e_{rn})$, we have:

$$[e_r] = [R][i] \tag{9}$$

Here $[R]$ is a square matrix of the nth order whose elements are the various mutual and self-resistance coefficients of the several meshes.

If we let F be the total instantaneous rate of energy loss of the circuit, we have:

$$F = [i]'[e_r] \tag{10}$$

Substituting (9) into (10), we have:

$$F = [i]'[R][i] \tag{11}$$

Consider now that the original n-mesh system is interconnected in some manner to form a transformed system. By the transformation there will be formed new meshes and consequently new mesh currents will be required to specify the transformed system.

Let the matrix of the new mesh currents be $[i]_n$, and let the new currents be related to the old currents by means of the transformation matrix $[A]$ which need not be nonsingular. That is:

$$[i] = [A][i]_n \tag{12}$$

In general, $[A]$ is an n-rowed matrix of constants.

Now in the new system, the form of the expressions:

$$T = \frac{[i]'[L][i]}{2} \tag{4}$$

$$V = \frac{[q]'[S][q]}{2} \tag{8}$$

$$F = [i]'[R][i] \tag{11}$$

must be preserved, and we must have:

$$T_n = [i]_n'[L]_n[i]_n/2 \tag{13}$$

$$V_n = [q]_n'[S]_n[q]_n/2 \tag{14}$$

$$F_n = [i]_n'[R]_n[i]_n \tag{15}$$

for the instantaneous magnetic energy, electrostatic energy, and power dissipation in the new system. Here $[L]_n$ is the new inductance matrix, $[S]_n$, the new elastance matrix, and $[R]_n$, the new resistance matrix.

To obtain the transformations of the new quantities from the old ones we use the equations:

$$[i] = [A][i]_n \tag{12}$$

$$[q] = [A][q]_n \tag{6}$$

Now, by one of the fundamental theorems of matrix algebra we have:

$$[i]' = ([A][i]_n)' = [i]_n'[A]' \tag{16}$$

$$[q]' = ([A][q]_n)' = [q]_n'[A]' \tag{17}$$

Substituting these expressions into the equations 4, 8, and 11, we obtain for the new network:

$$T_n = [i]_n'[A]'[L][A][I]_n/2 \tag{13}$$

$$V_n = [q]_n'[A]'[A][A][q]_n/2 \tag{14}$$

$$F_n = [i]_n'[A]'[R][A][i]_n \tag{15}$$

Hence if we place:

$$[L]_n = [A]'[L][A] \tag{18}$$

$$[S]_n = [A]'[S][A] \tag{19}$$

$$[R]_n = [A]'[R][A] \tag{20}$$

we preserve the form of the energy equations. We see that the new inductance, elastance, and resistance matrices are obtained from the old inductance, elastance, and resistance matrices by the same type of transformation involving the matrix $[A]$ and its transpose.

Transformation of the Impedance Matrix

The transformation of the impedance matrix is easily obtained by noting that:

$$[z]_n = [L]_n\frac{d}{dt} + [R]_n + [S]_n\int_{-\infty}^{t}(\ )dt \tag{21}$$

and

$$[z] = [L]\frac{d}{dt} + [R] + [S]\int_{-\infty}^{t}(\ )dt \tag{22}$$

In view of (18), (19), and (20), we see that:

$$[z]_n = [A]'[z][A] \tag{23}$$

is the transformation equation for the impedance operator matrix.

Transformation of the Mesh Voltages

In the new system, the canonical equations of the circuit may be written in the matrix form:

$$[e]_n = [z]_n[i]_n \tag{24}$$

or, in view of (23)

$$[e]_n = [A]'[z][A][i]_n \tag{25}$$

But

$$[i] = [A][i]_n \tag{12}$$

Hence:

$$[e]_n = [A]'[z][i] \tag{26}$$

However, by (1) $[e] = [z][i]$, therefore:

$$[e]_n = [A]'[e] \tag{27}$$

This is the transformation formula for the mesh voltages.

Transformation of Complex Quantities

Since the complex currents and voltages differ from the instantaneous currents and voltages only by scalar multiplicative phase constants, and the complex impedances differ from the impedance operators in that d/dt is replaced by jw and $\int_{-\infty}^{t}(\ )dt$ by $1/jw$, we see that these quantities transform in the same manner that the scalar instantaneous quantities transform, and hence we have that if:

$$[I] = [A][I]_n \tag{28}$$

that is, the complex voltages of the new system are linearly related to the complex voltages of the original system by the transformation matrix $[A]$, then:

$$[Z]_n = [A]'[Z][A] \tag{29}$$

and

$$[E]_n = [A]'[E] \tag{30}$$

III. Application to the General Wye-Wye Circuit

Let us apply the above theory to obtain the performance of the general wye-wye circuit of figure 1. For generality, we shall consider mutual inductance and capacitance between the three sending-end impedances, the four line impedances, and the three receiving-end impedances. We shall also assume that there are impressed voltages in series with the three sending-end impedances and the three receiving-end impedances.

The completed wye-wye circuit may be considered as made up by the synthesis of a ten-mesh network whose canonical equation is:

$$[e] = [z][i] \tag{1}$$

where:

$$[e] = \begin{array}{c|c} a & e_a \\ b & e_b \\ c & e_c \\ r & 0 \\ s & 0 \\ t & 0 \\ n & 0 \\ 1 & e_1 \\ 2 & e_2 \\ 3 & e_3 \end{array} \qquad [i] = \begin{array}{c|c} a & i_a \\ b & i_b \\ c & i_c \\ r & i_r \\ s & i_s \\ t & i_t \\ n & i_n \\ 1 & i_1 \\ 2 & i_2 \\ 3 & i_3 \end{array}$$

$$[z] = \begin{array}{c|cccccccccc} & a & b & c & r & s & t & n & 1 & 2 & 3 \\ a & z_{aa} & z_{ab} & z_{ac} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ b & z_{ba} & z_{bb} & z_{bc} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ c & z_{ca} & z_{cb} & z_{cc} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ r & 0 & 0 & 0 & z_{rr} & z_{rs} & z_{rt} & z_{rn} & 0 & 0 & 0 \\ s & 0 & 0 & 0 & z_{sr} & z_{ss} & z_{st} & z_{sn} & 0 & 0 & 0 \\ t & 0 & 0 & 0 & z_{tr} & z_{ts} & z_{tt} & z_{tn} & 0 & 0 & 0 \\ n & 0 & 0 & 0 & z_{nr} & z_{ns} & z_{nt} & z_{nn} & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & z_{11} & z_{12} & z_{13} \\ 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & z_{21} & z_{22} & z_{23} \\ 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & z_{31} & z_{32} & z_{33} \end{array}$$

This ten-mesh network is transformed into the wye-wye circuit of figure 1 by

interconnection. When the original network is interconnected, new meshes are formed and the old currents undergo certain constraints. If we let (i_a', i_b', i_c') be the currents flowing through the impedances z_{aa}, z_{bb}, and z_{cc} in the transformed network, we have the following equations giving the current constraints imposed on the old currents by the interconnection.

$$\left.\begin{array}{llll} i_a = i_a' & i_r = i_a' & i_1 = i_c' & i_2 = -i_b' \\ i_b = i_b' & i_s = i_b' & i_n = -(i_a' + i_b' + i_c') & \\ i_c = i_c' & & i_1 = -i_a' & i_3 = -i_c' \end{array}\right\} \quad (31)$$

That is, the old currents are linearly related to the new currents by the transformation matrix $[A]$, where in this case:

$$[A] = \begin{array}{c} \\ a \\ b \\ c \\ r \\ s \\ t \\ n \\ 1 \\ 2 \\ 3 \end{array} \begin{array}{c} \begin{array}{ccc} a' & b' & c' \end{array} \\ \left\|\begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & -1 & -1 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{array}\right\| \end{array} \quad (32)$$

$$[A]' = \left\|\begin{array}{cccccccccc} 1 & 0 & 0 & 1 & 0 & 0 & -1 & -1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & -1 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & -1 & 0 & 0 & -1 \end{array}\right\| \quad (33)$$

We now compute the new impedance matrix by means of the equation:

$$[z]_n = [A]'[z][A] \quad (23)$$

By direct multiplication, we have:

$$[z]_n = \left\|\begin{array}{ccc} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{array}\right\| \quad (34)$$

where:

$$\begin{array}{l} a_{11} = (z_{aa} + z_{rr} - 2z_{ar} + z_{nn} + z_{11}) \\ a_{22} = (z_{bb} + z_{ss} - 2z_{bs} + z_{nn} + z_{22}) \\ a_{33} = (z_{cc} + z_{tt} - 2z_{ct} + z_{nn} + z_{33}) \\ a_{12} = (z_{ab} + z_{rs} - z_{rn} - z_{ns} + z_{nn} + z_{12}) = a_{21} \\ a_{13} = (z_{ac} + z_{rt} - z_{rn} - z_{nt} + z_{nn} + z_{13}) = a_{31} \\ a_{23} = (z_{bc} + z_{st} - z_{sn} - z_{nt} + z_{nn} + z_{23}) = a_{32} \end{array}$$

We note that the new impedance matrix is symmetric. The new voltages are transformed by the equation:

$$[e]_n = [A]'[e] \quad (27)$$

In this case, by direct multiplication, we obtain:

$$[e]_n = \left\|\begin{array}{c} (e_a - e_1) \\ (e_b - e_2) \\ (e_c - e_3) \end{array}\right\| \quad (35)$$

We then have:

$$[e]_n = [z]_n[i]_n \quad (24)$$

or:

$$[i]_n = [z]_n^{-1}[e]_n \quad (36)$$

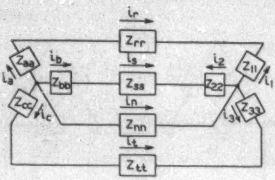

Figure 1. General wye-wye circuit

Z_{ab} is the mutual impedance between Z_{aa} and Z_{bb}, etc.

or placing:

$$[y]_n = [z]_n^{-1} \quad (37)$$

we have:

$$[i]_n = [y]_n[e]_n \quad (38)$$

Calculating the inverse of the matrix (34), we obtain:

$$[y]_n = \frac{1}{D}\left\|\begin{array}{ccc} (a_{22}a_{33} - a_{23}^2) & (a_{32}a_{13} - a_{12}a_{33}) & (a_{12}a_{23} - a_{22}a_{13}) \\ (a_{31}a_{23} - a_{21}a_{33}) & (a_{11}a_{33} - a_{13}^2) & (a_{21}a_{13} - a_{11}a_{23}) \\ (a_{21}a_{32} - a_{31}a_{22}) & (a_{31}a_{12} - a_{11}a_{32}) & (a_{11}a_{22} - a_{12}^2) \end{array}\right\| \quad (39)$$

and D is the determinant

$$D = \left|\begin{array}{ccc} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{array}\right|$$

we note that the matrix $[y]_n$ is symmetric.

The currents in the various elements are now obtained from:

$$[i] = [A][i]_n \quad (12)$$

The equation $[e]_n = [Z]_n[i]_n$ may be given a rather interesting physical interpretation. If we write:

$$[e]_s = \left\|\begin{array}{c} e_a \\ e_b \\ e_c \end{array}\right\| \quad (40) \qquad [e]_r = \left\|\begin{array}{c} e_1 \\ e_2 \\ e_3 \end{array}\right\| \quad (41)$$

$$[z]_s = \left\|\begin{array}{ccc} z_{aa} & z_{ab} & z_{ac} \\ z_{ba} & z_{bb} & z_{bc} \\ z_{ca} & z_{cb} & z_{cc} \end{array}\right\| \quad (42)$$

$$[z]_r = \left\|\begin{array}{ccc} z_{11} & z_{12} & z_{13} \\ z_{21} & z_{22} & z_{23} \\ z_{31} & z_{32} & z_{33} \end{array}\right\| \quad (43)$$

$$[z]_L = \left\|\begin{array}{ccc} (z_{rr} - 2z_{rn} + z_{nn}) & (z_{rs} - z_{rn} - z_{ns} + z_{nn}) & (z_{rt} - z_{rn} - z_{nt} + z_{nn}) \\ (z_{sr} - z_{sn} - z_{nr} + z_{nn}) & (z_{ss} - 2z_{sn} + z_{nn}) & (z_{st} - z_{sn} - z_{nt} + z_{nn}) \\ (z_{tr} - z_{tn} - z_{nr} + z_{nn}) & (z_{ts} - z_{tn} - z_{ns} + z_{nn}) & (z_{tt} - 2z_{nt} + z_{nn}) \end{array}\right\| \quad (44)$$

Then, we may write:

$$[e]_s = [z]_s[i]_n + [z]_L[i]_n + [z]_r[i]_n + [e]_r \quad (45)$$

This equation is the same as that of a simple series circuit with the exception that the ordinary voltages, impedances, and current are replaced by matrix quantities.

The Steady State

In the above analysis, we have considered the transformation of the instantaneous voltages, currents, and the impedance operators. In case the impressed voltages at the sending and receiving ends are sinusoidal quantities of arbitrary phase, all the foregoing equations hold when the instantaneous voltage matrix, $[e]$, is replaced by the vector voltage matrix, $[E]$, the instantaneous current matrix, $[i]$, is replaced by the vector current matrix, $[I]$, and the impedance operator matrix, $[z]$, is replaced by the complex impedance matrix, $[Z]$.

We have, then, the equation:

$$[I]_n = [Z]^{-1}[E]_n = [Y]_n[E]_n \quad (46)$$

for the determination of the vector currents in terms of the complex admittance matrix and the complex voltage matrix. The impedance matrix $[Y]_n$ is given by (39) where the a's have the values given in (34) and the z's are replaced by the Z's or complex impedance operators.

Transient Disturbances (General Electromotive Forces)

Having obtained the equation of the circuit in the canonical form:

$$[e]_n = [z]_n[i]_n \quad (24)$$

we may proceed to find the response of the circuit to the effect of arbitrary electromotive forces impressed at $t=0$ by the use of the Laplacian transformation (see reference 2). In order to do this,

$$[E(p)]_n = p\int_0^\infty e^{-pt}[e]_n dt \quad (47)$$

$$[I(p)]_n = p\int_0^\infty e^{-pt}[i]_n dt \quad (48)$$

Then if we take (24) and multiply both sides by $pe^{-pt}dt$ and integrate them from zero to infinity, we have:

$$p\int_0^\infty e^{-pt}[e]_n dt = p\int_0^\infty e^{-pt}[z]_n[i]_n dt \quad (49)$$

Now since:

$$[z]_n = [L]_n\frac{d}{dt} + [R]_n + [S]_n\int_{-\infty}^{t}(\ )dt \quad (21)$$

we may transform (49) by integrating by parts and we obtain:

$$[Z(p)]_n[I(p)]_n = [E(p)]_n + p[L]_n[i^0]_n - [S]_n[q^0]_n \quad (50)$$

where $[i^0]_n$ is a columnar matrix giving the initial currents in the mesh inductances at $t = 0$. $[q^0]_n$ is a columnar matrix giving the initial charges in the mesh elastances at $t = 0$. $[Z(p)]$ is a matrix whose elements are:

$$Z_{mn} = pL_{mn} + R_{mn} = S_{mn}/p \tag{51}$$

If we multiply (50) by $[Z(p)]_n^{-1}$, we get:

$$[I(p)]_n = [Z(p)]_n^{-1}([E(p)]_n + p[L]_n[i^0]_n - [S]_n[q^0]_n) \tag{52}$$

Now, by means of the Fourier-Mellin inversion formula, we have an explicit expression for the instantaneous current matrix:

$$[i(t)]_n = \frac{1}{2\pi j}\int_{c-j\infty}^{c+j\infty} \frac{e^{pt}[I(p)]_n dt}{p} \tag{53}$$

and we have a formal solution for the circuit currents when arbitrary electromotive forces, initial currents, and initial charges are impressed upon the circuit at $t=0$.

IV. The Delta-Delta Circuit

We shall now carry out a similar treatment of the general delta-delta circuit shown in figure 2. We shall consider electromotive forces in series with the three delta-connected impedances at the sending end, electromotive forces in series with the three delta-connected impedances at the receiving end, and also mutual inductances and capacitances will be assumed between the three sending-end impedances, the three receiving-end impedances, and the three line impedances.

The delta-delta circuit may be considered as made up by the synthesis of a nine-mesh circuit which is interconnected to form the required four-mesh delta-delta circuit.

The impedance matrix of the original nine-mesh circuit is:

$$[z] = \begin{Vmatrix} z_{aa} & z_{ab} & z_{ac} & 0 & 0 & 0 & 0 & 0 & 0 \\ z_{ba} & z_{bb} & z_{bc} & 0 & 0 & 0 & 0 & 0 & 0 \\ z_{ca} & z_{cb} & z_{cc} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & z_{rr} & z_{rs} & z_{rt} & 0 & 0 & 0 \\ 0 & 0 & 0 & z_{sr} & z_{ss} & z_{st} & 0 & 0 & 0 \\ 0 & 0 & 0 & z_{tr} & z_{ts} & z_{tt} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & z_{11} & z_{12} & z_{13} \\ 0 & 0 & 0 & 0 & 0 & 0 & z_{21} & z_{22} & z_{23} \\ 0 & 0 & 0 & 0 & 0 & 0 & z_{31} & z_{32} & z_{33} \end{Vmatrix} \tag{54}$$

In order to specify the interconnected delta-delta circuit, we shall use the four mesh currents (i_1', i_2', i_3', i_4') shown in figure 2. The elements of the transformation matrix, $[A]$, are obtained from the set of equations:

$$\begin{array}{lll} i_a = i_1' - i_4' & i_r = i_3' & i_1 = i_2' + i_3' \\ i_b = i_1' - i_4' & i_s = i_4' - i_3' & i_2 = i_2' + i_4' \\ i_c = i_1' & i_t = -i_4' & i_3 = i_3' \end{array} \tag{55}$$

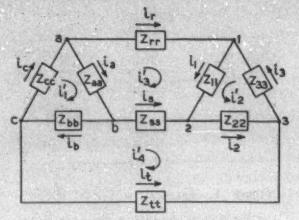

Figure 2. General delta-delta circuit

Hence the transformation matrix is:

$$[A] = \begin{Vmatrix} 1 & 0 & -1 & 0 \\ 1 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 1 \\ 0 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 \end{Vmatrix} \tag{56}$$

$$[A]' = \begin{Vmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ -1 & 0 & 0 & 1 & -1 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 0 & 1 & -1 & 0 & 1 & 0 \end{Vmatrix} \tag{57}$$

By direct multiplication using the equation:

$$[z]_n = [A]'[z][A], \tag{23}$$

we obtain

$$[z]_n = \begin{Vmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{Vmatrix} \tag{58}$$

where:

$$\begin{aligned} a_{11} &= z_{aa} + z_{bb} + z_{cc} + 2z_{ab} + 2z_{ac} + 2z_{bc} \\ a_{22} &= z_{11} + z_{22} + z_{33} + 2z_{12} + 2z_{13} + 2z_{23} \\ a_{33} &= z_{aa} + z_{rr} + z_{ss} + z_{11} - 2z_{rs} \\ a_{44} &= z_{bb} + z_{ss} + z_{tt} + z_{22} - 2z_{ts} \\ a_{12} &= a_{21} = 0 \\ a_{13} &= -(z_{aa} + z_{ba} + z_{ca}) = a_{31} \\ a_{14} &= -(z_{ab} + z_{bb} + z_{cb}) = a_{41} \\ a_{23} &= z_{11} + z_{21} + z_{31} = a_{32} \\ a_{24} &= z_{12} + z_{22} + z_{32} = a_{42} \\ a_{34} &= z_{ab} + z_{rs} - z_{as} + z_{s1} - z_{rs} + z_{12} = a_{43} \end{aligned}$$

The original voltage matrix is:

$$[e] = \begin{Vmatrix} e_a \\ e_b \\ e_c \\ 0 \\ 0 \\ 0 \\ e_1 \\ e_2 \\ e_3 \end{Vmatrix} \tag{59}$$

$$[e]_n = [A]'[e] = \begin{Vmatrix} (e_a + e_b + e_c) \\ (e_1 + e_2 + e_3) \\ (-e_a + e_1) \\ (-e_b + e_3) \end{Vmatrix} \tag{60}$$

The transformed voltage matrix.

We now have:

$$[i]_n = [z]_n^{-1}[e]_n \tag{36}$$

the formal expression for the various mesh currents.

The treatment for the steady-state and transient behavior may be carried out in the manner discussed in part III.

V. The Delta-Wye Circuit

Let us consider the delta-wye circuit shown in figure 3. As in the above examples, we may consider this circuit as made up by the synthesis of a nine-mesh circuit whose impedance matrix is given by (54).

The delta-wye circuit will be specified by the three mesh currents (i_1', i_2', i_3') as shown in the figure. In this case, the elements of the transformation matrix are given by the set of equations giving the following current constraints:

$$\begin{array}{lll} i_a = i_1' - i_2' & i_r = i_2' & i_1 = i_3' \\ i_b = i_1' - i_3' & i_s = i_3' - i_2' & i_2 = i_2' - i_3' \\ i_c = i_1' & i_t = -i_3' & i_3 = i_3' \end{array}$$

Hence we have the following transformation matrix:

$$[A] = \begin{Vmatrix} 1 & -1 & 0 \\ 1 & 0 & -1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & -1 & 1 \\ 0 & 0 & -1 \\ 0 & -1 & 0 \\ 0 & 1 & -1 \\ 0 & 0 & 1 \end{Vmatrix} \tag{62}$$

$$[A]' = \begin{Vmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & -1 & 0 & -1 & 1 & 0 \\ 0 & -1 & 0 & 0 & 1 & -1 & 0 & -1 & 1 \end{Vmatrix} \tag{63}$$

By the equation:

$$[z]_n = [A]'[a][A] \tag{23}$$

we obtain the transformed matrix:

$$[z]_n = \begin{Vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{Vmatrix} \tag{64}$$

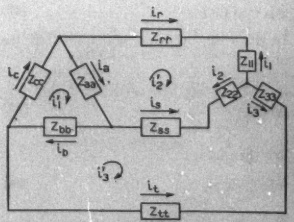

Figure 3. General delta-wye circuit

where:

$$\begin{aligned}
a_{11} &= z_{aa}+z_{bb}+z_{cc}+2z_{ab}+2z_{ac}+2z_{cb}\\
a_{22} &= z_{aa}+z_{rr}+z_{ss}+z_{sr}-2z_{sr}-2z_{rs}+z_{11}\\
a_{33} &= z_{bb}+z_{ss}+z_{rr}+z_{sr}+z_{rs}-2z_{rs}-2z_{sr}\\
a_{12} &= -(z_{ac}+z_{cb}+z_{ca}) = a_{21}\\
a_{13} &= -(z_{ab}+z_{bb}+z_{cb}) = a_{31}\\
a_{23} &= (z_{ab}+z_{rb}-z_{sb}-z_{rr}+z_{sr}+z_{rs}-z_{ar}-z_{as}+ z_{ss}) = a_{32}
\end{aligned} \tag{65}$$

The inverse matrix:

$$[y]_n = [z]_n^{-1} \tag{37}$$

is given in terms of the a's by (39) where in this circuit, the a's have the values given by (65).

In this case, the original voltage matrix is given by (59) and by the transformation we obtain:

$$[e]_n = [A]'[e] = \left\| \begin{matrix} (e_a+e_b+e_c) \\ (e_b-e_a-e_1) \\ (e_c-e_b-e_2) \end{matrix} \right\| \tag{66}$$

The various mesh currents are given by:

$$[i]_n = [z]_n^{-1}[e]_n \tag{36}$$

and the solution for the steady state or the transient behavior follows the same reasoning of part III.

It is noted that by considering these general cases, we have covered all possible combinations of delta and wye connections. In the case that the circuits have balanced impedances and voltages, considerable simplifications are effected in the above general equations. In case even more general circuits are considered, the matrices of the original nine or ten mesh circuits whose synthesis produce the required circuits would have mutual impedances between every mesh. The synthesis of such networks would produce polyphase systems having coupling between every elements. The amount of coupling considered here is sufficiently general for practical purposes.

VI. Symmetrical Components

The discussion will be concluded with a brief consideration of the transformation theory of the method of symmetrical components. Since the method of symmetrical components is one of linear transformation, it lends itself readily to matrix formulation.

In the method of symmetrical components, the transformations are effected by the use of the nonsingular, symmetric matrix:

$$[S] = \left\| \begin{matrix} 1 & 1 & 1 & . & . & . & 1 \\ 1 & a^{-1} & a^{-2} & . & . & . & a^{-(n-1)} \\ 1 & a^{-2} & a^{-4} & . & . & . & a^{-2(n-1)} \\ . & . & . & . & . & . & . \\ 1 & a^{-(n-1)} & a^{-2(n-1)} & . & . & . & a^{-(n-1)(n-1)} \end{matrix} \right\| \tag{67}$$

where:

$$a = e^{2\pi j/n} \tag{68}$$

The matrix $[S]$ may be written more briefly in the manner:

$$[S] = \left\| \begin{matrix} S_0 \\ S_{-1} \\ S_{-2} \\ - \\ S_{-(n-1)} \end{matrix} \right\| \tag{69}$$

where:

$$S_{-r} = (1,\ a^{-r},\ a^{-2r},\ \ldots\ a^{-(n-1)r}) \tag{70}$$

is the same as Fortescue's sequence operator S^r.

Fundamental Properties of [S]

Inspection of the matrix $[S]$, reveals that it has the following important properties:

$$[S]' = [S] \tag{71}$$

where $[S]$ is the transpose of $[S]$

$$[S]^{-1} = \frac{1}{n}[\overline{S}] \tag{72}$$

where $[S]^{-1}$ is the inverse of $[S]$ and $[\overline{S}]$ is the conjugate of $[S]$ given by:

$$[\overline{S}] = \left\| \begin{matrix} S_0 \\ S_1 \\ S_2 \\ - \\ S_{(n-1)} \end{matrix} \right\|$$

and n is the order of $[S]$.

Transformation of Voltages and Currents

Let the ordinary complex voltages and currents of an n-phase network be written in the form:

$$[I] = \left\| \begin{matrix} I_1 \\ I_2 \\ - \\ I_n \end{matrix} \right\| \tag{73} \qquad [E] = \left\| \begin{matrix} E_1 \\ E_2 \\ - \\ E_n \end{matrix} \right\| \tag{74}$$

and let $[I]_s$ and $[E]_s$ be the symmetrical components of current and voltage respectively. They are specified by the equations:

$$[i] = [S][I]_s \tag{75}$$

$$[E] = [S][E]_s \tag{76}$$

Or, since $[S]$ is a nonsingular matrix, its inverse exists and we have:

$$[I]_s = [S]^{-1}[i] = \frac{1}{n}[\overline{S}][I] \tag{77}$$

$$[E]_s = [S]^{-1}[E] = \frac{1}{n}[\overline{S}][E] \tag{78}$$

Transformation of Impedances and Admittances

The impedance matrix $[Z]$ associated with the ordinary currents $[I]$ and the ordinary voltages $[E]$ satisfies the equation:

$$[E] = [Z][I] \tag{79}$$

or

$$[S][E]_s = [Z][S][I]_s \tag{80}$$

Hence:

$$[E]_s = [S]^{-1}[Z][S][I]_s \tag{81}$$

If we place:

$$[Z]_s = [S]^{-1}[Z][S] \tag{82}$$

the symmetrical component matrix, then we have:

$$[E]_s = [Z]_s[I]_s \tag{83}$$

the voltage equation in symmetrical components.

From (82) we see that $[Z]_s$ is obtained from $[S]$ by a similarity transformation. We have also the reciprocal relation:

$$[Z] = [S][Z]_s[S]^{-1} = \frac{1}{n}[S][Z]_s[\overline{S}]$$

By the fundamental definition of the admittance matrix, we have:

$$[Y]_s = [Z]_s^{-1} = ([S]^{-1}[Z][S])^{-1} \tag{84}$$

Now, by a fundamental theorem of matrix algebra, if A, B, and C are nonsingular matrices, then:

$$(ABC)^{-1} = C^{-1}B^{-1}A^{-1}$$

Applying this to (84), we obtain:

$$[Y]_s = [S]^{-1}[Z]^{-1}[S]^{-1} \tag{85}$$

But $[Z]^{-1} = [Y]$, hence:

$$[Y]_s = [S]^{-1}[Y][S] = \frac{1}{n}[\overline{S}][Y][S] \tag{86}$$

and we have the reciprocal relation:

$$[Y] = [S][Y]_s[S]^{-1} = \frac{1}{n}[S][Y]_s[\overline{S}] \tag{87}$$

We see from this that the symmetrical component impedance and admittance matrices are derived from the ordinary impedance and admittance matrices by similarity transformations.

Transformation of the Vector Volt-Ampere Input

The vector volt-ampere input P in terms of the original voltages and currents of the system is defined by the equation:

$$P = [I]'[\overline{E}] \tag{88}$$

Now by (75) and (76), this transforms into:

$$P = ([S][I]_s)'[\overline{S}][\overline{E}]_s \tag{89}$$

But $([S][I_n])' = [I_n]'[S]'$ by a fundamental theorem.

Hence:

$$P = [I_n]'[S]'[\bar{S}][\bar{E}]_n \tag{90}$$

Now $[\bar{S}] = n[S]^{-1}$, $[S]' = [S]$, hence:

$$P = [I_n]'[S]n[S]^{-1}[\bar{E}]_n = n[I_n]'[\bar{E}]_n \tag{91}$$

But by definition, the vector volt-ampere input in the symmetrical component quantities is:

$$P_s = [I]_n'[\bar{E}]_n \tag{92}$$

hence:

$$P = nP_s \tag{93}$$

And we see that the actual vector volt-ampere input to the system is n times the amount as calculated by (92) where n is the order of the phase of the system.

VII. Symmetrical Components in General Wye-Wye Circuit

If we write (45) in terms of complex voltages, impedances, and current, we have:

$$[E]_s = [Z]_s[I]_n + [Z]_L[I]_n + [Z]_r[I]_n + [E]_r \tag{94}$$

Let us multiply this equation by $[S]^{-1}$, we then obtain:

$$\begin{aligned}[S]^{-1}[E]_s = {} & [S]^{-1}[Z]_s[S][S]^{-1}[I]_n + \\ & [S]^{-1}[Z]_L[S][S]^{-1}[I]_n + \\ & [S]^{-1}[Z]_r[S][S]^{-1}[I]_n + [S]^{-1}[E]_r\end{aligned} \tag{95}$$

If we now introduce:

$[S]^{-1}[E]_s = [E]_{ss}$ the symmetrical component matrix of sending-end voltages (96)

$[S]^{-1}[E]_r = [E]_{rs}$ the symmetrical component matrix of receiving-end voltages (97)

$[I]_{ns} = [S]^{-1}[I]_n$ a matrix whose elements are the symmetrical components of line currents (98)

$[Z]_{ss} = [S]^{-1}[Z]_s[S]$ the symmetrical component matrix of sending-end impedances (99)

$[Z]_{Ls} = [S]^{-1}[Z]_L[S]$ the symmetrical component matrix of line impedances (100)

$[Z]_{rs} = [S]^{-1}[Z]_r[S]$ the symmetrical component matrix of receiving-end impedances (101)

then (95) becomes:

$$[E]_{ss} = [Z]_{ss}[I]_{ns} + [Z]_{Ls}[i]_{ns} = [Z]_{rs}[I]_{ns} + [E]_{rs} \tag{102}$$

and we have explicitly:

$$[I]_{ns} = ([Z]_{ss} + [Z]_{Ls} + [Z]_{rs})^{-1}([E]_{ss} - [E]_{rs}) \tag{103}$$

an equation for the determination of the symmetrical components of line currents. It may be noted that in case the generator and receiver voltages are balanced, a considerable simplification will be effected.

The currents in the various parts of the system are given by:

$$[I] = [A][I]_n \tag{28}$$

If we multipy this equation by $[S]^{-1}$, we obtain:

$$[S]^{-1}[I] = [S]^{-1}[A][S][S]^{-1}[I]_n \tag{104}$$

If we place:

$[I]_s = [S]^{-1}[I]$ the symmetrical component matrix of the currents in the various parts of the system (105)

$[A]_s = [S]^{-1}[A][S]$ the symmetrical component transformation matrix (106)

then (104) may be written in the form:

$$[I]_s = [A]_s[I]_{ns} \tag{107}$$

and we see that the symmetrical component matrix of the currents in the various parts of the system are obtained from the symmetrical component matrix of the line currents by means of a transformation matrix $[A]_s$, obtained from the ordinary transformation matrix $[A]$ by means of a similarity transformation.

VIII. Conclusion

The simplicity by means of which general expressions for complex networks are obtained by the use of matrix notation and transformation theory is apparent from the above examples. The systematization made possible by concise matrix manipulation makes the algebraic work a minimum and the trend of the argument is brought clearly into the foreground.

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Discussion

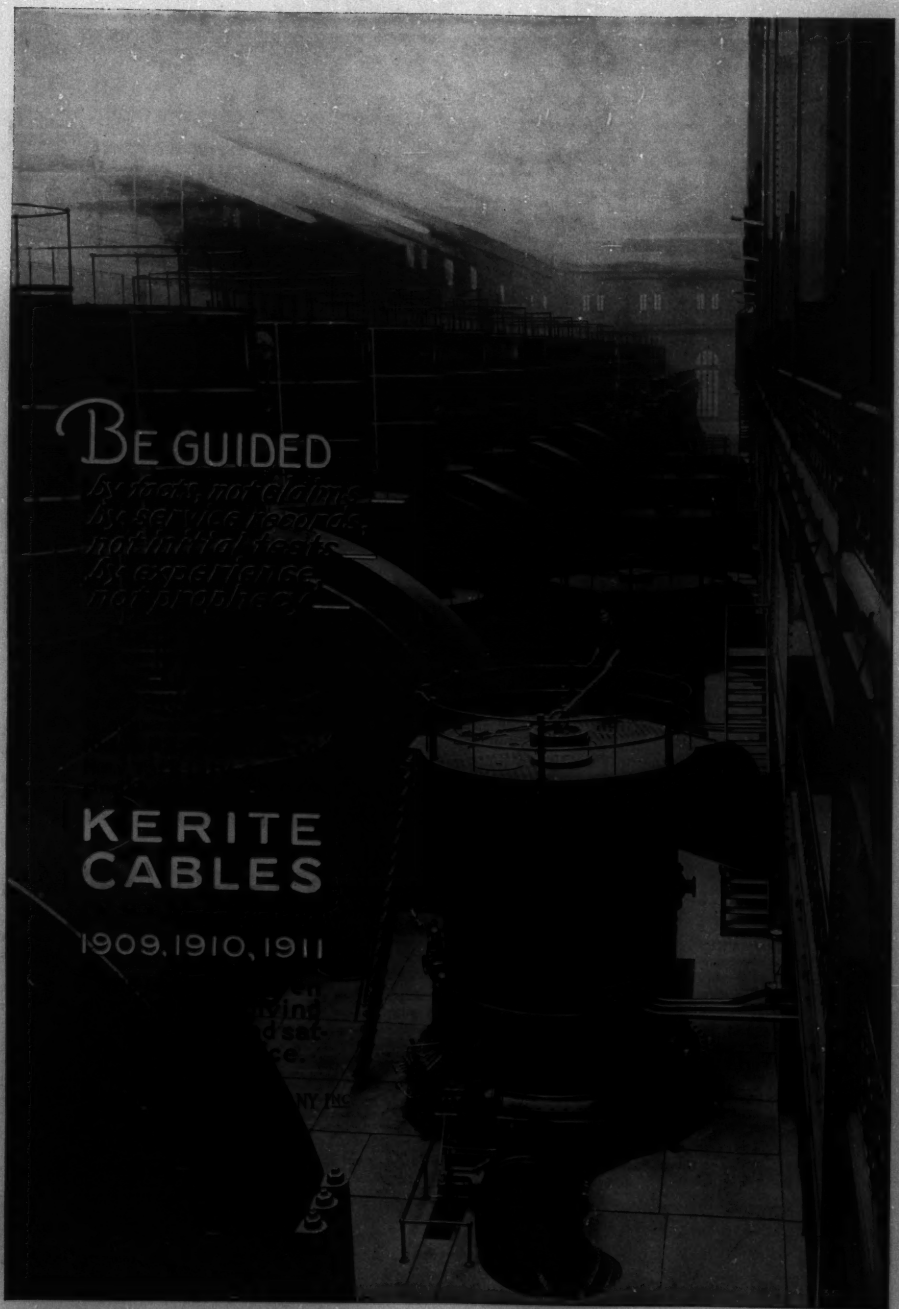
Myril B. Reed (Armour Institute of Technology, Chicago, Ill.): The concept of an *old* space, or mesh system, in which a network may be represented in a so-called generalized form, and from which, by means of a transformation matrix, the generalized impedance matrix may be transformed into the impedance matrix of the connected, or *new* space, network has been developed and used as the basis of the extensive work on static networks and machines written by Kron. Pipes has used this same concept.

In writing the introductory work preliminary to the application of tensors, the transformation from one space to another is not only pertinent but essential, since tensor analysis is based on transforming from one space to another. Even so, it should be pointed out that insofar as static networks are concerned the tensor concept and, therefore, transformation from an old to a new space is not necessary. In fact the C matrix of Kron and the A matrix of Pipes are somewhat artificial when applied to static-network theory. These transformations are used to establish the impedance matrix for the physical network. But this may be done rather easily by means of Kirchhoff's voltage equations in terms of Maxwell's cyclic currents, and the *old* and *new* spaces, or mesh systems, do not make the impedance matrix easier to form, understand, or use.

However, the idea of matrix transformations is useful, and can be used effectively in many ways as the papers indicated in the bibliography of Pipes' paper demonstrate. The pure mathematician has developed an extensive theory of matrices and matrix transformations which may be borrowed whole-cloth as it were, and applied to the manipulation of the set of linear equations expressing the properties of an electric circuit; and from these manipulations we may expect to reach conclusions formerly hidden by the very fact that the Kirchhoff equations are many, and, therefore, difficult to manipulate as a unit.

Louis A. Pipes: Professor Reed, in his discussion, points out that the transformation concept is used to establish the impedance matrix of the physical network and that this may be done more easily by means of a direct application of Kirchhoff's equations. For simple systems involving only a few mutual coupling coefficients, this is perhaps true. However, in complex systems, there is a very great danger that in setting up the Kirchhoff equations certain terms may be omitted because of the complexity of the problem. Once the generalized impedance matrix is written down, however, the actual impedance matrix of the system may be easily obtained without further thought on the part of the analyst by means of the "constraint" matrix, A. The philosophy of the method is very similar to the use of the Lagrangian equations in dynamics to obtain the equations of motion of dynamical systems when the energy and dissipation functions are known.

That the concept of matrix transformation is useful in electrical circuit theory has by now been amply demonstrated by the numerous papers on its application to this field which have appeared recently.


BE GUIDED
by facts, not claims
by service records
not initial tests
by experience
not prophecy
KERITE
CABLES
1909, 1910, 1911

THE small compact size and light weight of the I. T. & T. Selenium Rectifier is the design engineer's dream. Because the high permissible voltage of the plates holds to a minimum the number required . . . the high current density permits the use of small plates . . . and the one-piece plate minimizes the number of parts, the Selenium Rectifier is inherently a small unit for its high power-handling capacity.

The use of small hardware, including lighter mounting brackets, is made possible by light assembly pressure. The compactness permits reduction in the size and gauge of housings—thus adding to flexibility of design and reduction in costs.

Other Outstanding Features of I. T. & T. Selenium Rectifiers

The I. T. & T. Selenium Rectifier finds wide, general-purpose application in a variety of forms for the rectification of high or low currents at high or low voltages. It also has many other uses, such as: a spark quencher, polarizer, tone generator, etc.

Efficiency: In addition to low first cost, the high efficiency of the Selenium Rectifier over a wide load range assures economical operation and, furthermore, it requires no maintenance.

Wide Temperature Range: It operates instantly in ambient temperatures of from —40°C. to +75°C. for continuous service — higher for intermittent.

Overload Capacity: It will withstand short overloads of ten or more times the normal rated current without damage.

Ruggedness: It is entirely metallic, rugged in design and construction—unaffected by shock or vibration. Not critical to assembly pressure.

Regulation: Stable output and good regulation during years of wide use.

Electrical Stability: It has no moving parts, it requires no adjustments or replacements, there is nothing to get out of order. It has practically unlimited life.

Low Back Leak: It has negligible back leak for battery charging. No protective devices required to guard against interruptions in A.C. supply.

Consulting engineering services available for your specific requirements.
Address Technical Department for descriptive bulletin.

INTERNATIONAL TELEPHONE DEVELOPMENT CO., INC.
137 Varick Street, New York, N. Y.

HERE'S A NEW G-E DELTABESTON RESISTOR CABLE

AND HERE'S HOW THE GENERAL ELECTRIC COMPANY USES IT

When resistors are bound to get hot, they ought to be wired with this new Deltabeston Resistor Cable. That's what the General Electric Company of Schenectady thinks after using it for this purpose for over eighteen months.

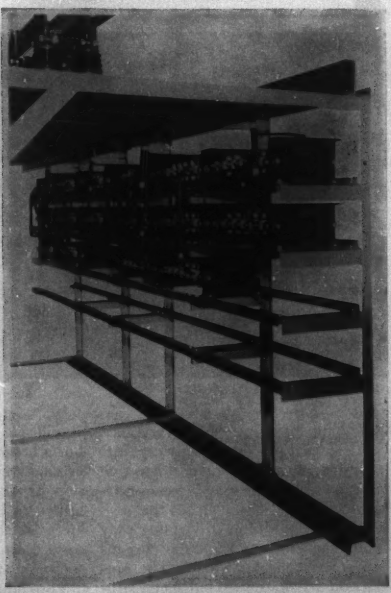
If you examine the insulation you'll see why. Over the extremely flexible tinned copper conductor is a Flamenol tape wrap. Flamenol is today the outstanding heat-resisting type of synthetic insulation.

Immediately over the Flamenol tape is a layer of felted asbestos (purified by the exclusive Deltabeston Purification Process). This asbestos is impregnated with a heat-, moisture-, and flame-resisting compound.

Add to this the asbestos braid, saturated with a heat and moisture-resisting finish and then wiped clean and smooth. Now you can see why heat and moisture can't break down this Deltabeston Resistor Cable.

Available in sizes 4/0 to 14 with solid conductor — sizes 1,000,000 CM to 14 with stranded conductors.

We'll be happy to send you a sample of this new Deltabeston Resistor Cable—and a catalog, too. Just write to Section Y-0492, Appliance & Merchandise Department, General Electric Co., Bridgeport, Connecticut.



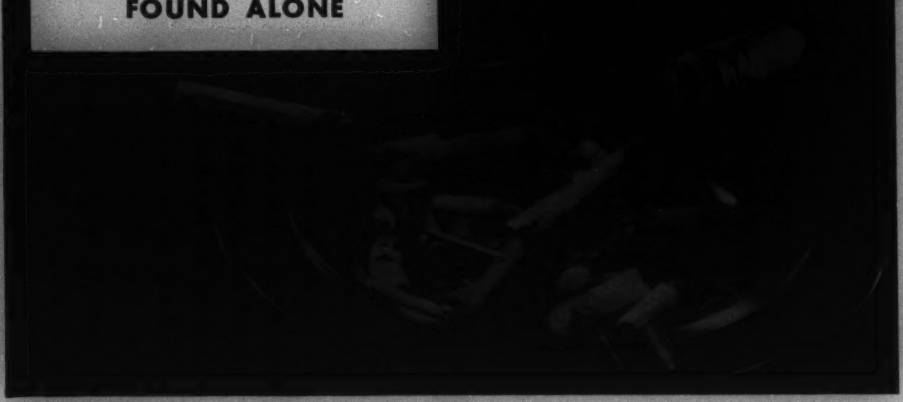
Deltabeston Wires and Cables are sold by all G-E Merchandise Distributors and by Graybar Electric Co.

GENERAL ELECTRIC

A PROBLEM IN ELECTRICAL STEEL

goes up in Smoke

AS TWO MEN EASILY FIND AN ANSWER THAT NEITHER COULD HAVE FOUND ALONE



IT happens somewhere every day. An electrical manufacturer runs into a lamination production problem that he knows the *right* steel recommendation will solve. He calls in the man from Carnegie-Illinois. Together they study the problem, each applying his own specialized knowledge. The production man knows his particular situation thoroughly. The Carnegie-Illinois engineer contributes not only a specialized knowledge of silicon steels, but a broad familiarity with electrical production in many fields. A discussion between these two men usually brings to light sound, money-saving ideas which help to keep production costs down to a minimum and often result in an improved product.

Throughout the industry, manufacturers have come to rely on the recommendations of the man from Carnegie-Illinois. He's trained to know Electrical Steel Sheets and to solve problems involving their use. He has at his command the research, production and distribution facilities of the foremost steel producer in the world. He handles every type of Electrical Steel Sheet and can make unbiased suggestions without favoring any one product.

Why not discuss with him your next problem that involves the use of steel?

USS

ELECTRICAL STEEL SHEETS

CARNEGIE-ILLINOIS STEEL CORPORATION

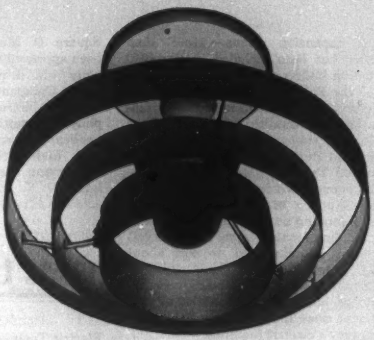
Pittsburgh and Chicago

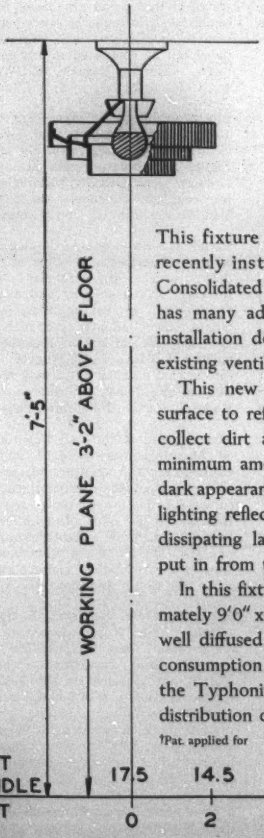
Columbia Steel Company, San Francisco, *Pacific Coast Distributors*
United States Steel Export Company, New York

UNITED STATES STEEL

*TYPHONITE ELDORADO PENCIL PAGE

NEW, INDIRECT LUMINAIRE IMPROVES DRAFTING-ROOM ILLUMINATION





This fixture was developed for a lighting system recently installed in a large drafting room of the Consolidated Edison Company of New York, Inc. It has many advantages over present fixtures, and its installation does not require extensive alterations of existing ventilation, conduit and wiring systems.

This new unit† presents a minimum intercepting surface to reflected light from the ceiling—does not collect dirt and dead insects; therefore requires a minimum amount of cleaning—does not present the dark appearance usually found on under side of indirect lighting reflectors—provides excellent ventilation for dissipating lamp filament heat—new lamps can be put in from the floor with lamp changer.

In this fixture 200-watt lamps installed on approximately 9'0" x 6'0" centers produce 38-foot candles of well diffused light on the working plane at a power consumption of only 3.8 watts per square foot. In the Typhonite Eldorado drawing the figures show distribution curve for one fixture.

†Pat. applied for

*TYPHONITE is a new form of natural graphite, used exclusively by Dixon in making leads for Eldorado pencils. Typhonite consists of extremely minute particles of controlled size produced by a whirlwind or typhoon of dry steam. This new exclusive Dixon process is one of the reasons why Eldorado pencils hold their points longer, give off freely, and make such opaque lines and figures.

FREE—A blueprint from original Typhonite Eldorado drawings, giving essential installation and other important data concerning this new unit, will be sent upon request. Just write on professional letterhead to address below. Ask for blueprint No. 42-J2 (Note—This offer is good for 30 days after appearance of this advertisement.)

PENCIL SALES DEPARTMENT, JOSEPH DIXON CRUCIBLE CO., JERSEY CITY, N. J.

Industrial Notes

Utility's Expansion Plans.—More than $9,000,000 has been included in the 1940 construction budget for the electric department of the Public Service Corporation of New Jersey. Major items include a switching station near Camden and high voltage steel tower transmission lines between Camden and Burlington and between Burlington and Trenton. More than $1,000,000 will be expended for continuance of the company's policy of placing transmission lines underground on main business streets. A new building for the testing laboratory at Irvington is contemplated, to cost about $400,000. Over $53,000,000, a considerable portion of which has already been expended has been allocated to the electric department since 1937 for the expansion of the company's electric facilities.

Roebling Appointment.—Charles G. Williams, formerly vice-president in charge of purchasing and manufacturing operations for the plants of the American Chain & Cable Company, Inc., has been appointed general manager of the John A. Roebling's Sons Company, Trenton, N. J. Mr. Williams will assume his new duties on March 1.

Precision Bearings, Inc. Promotes.—Harold Swanton has been elected vice-president of Precision Bearings, Inc., of Los Angeles, Calif., succeeding Norman Bell, who has resigned. Mr. Swanton, who has been sales manager of the company for several years will continue in that capacity, in addition to his new duties as vice-president.

General Electric Orders Up.—Orders received by the General Electric Company, during the fourth quarter of 1939 amounted to $112,166,535, compared with $63,419,265, in the final quarter of 1938, an increase of 77 per cent. For the year 1939, orders amounted to $360,748,386, compared with $252,176,223 for 1938, an increase of 43 per cent. Sales billed and net earnings are not yet available.

Copperweld Steel Appointment.—Sidney D. Williams has been appointed vice-president and in charge of sales of the Copperweld Steel Company's new steel division at Warren, Ohio. Mr. Williams was previously director of sales for the Timken Steel and Tube division of the Timken Roller Bearing Company, Canton, Ohio.

Large Motor Order to Westinghouse.—A contract for 18 auxiliary motors with a combined output of 14,800 horsepower, costing approximately $121,000, has been awarded to the Westinghouse Electric & Mfg. Company., by the Public Service Electric & Gas Company, of Newark, N. J. Designed for the operation of boiler feed, condensate and circulating pumps and other power station equipment, the motors range in rating from 200 to 1350 horsepower. They will be installed in the new extensions at the Marion and Burlington power stations late in 1940.

Square D Merger.—A merger plan has been approved whereby the Square D Company will acquire the Kollsman Instrument Company, Inc., manufacturers of aircraft instruments. The latter company will continue to operate as an independent unit, with its instruments made and sold under the Kollsman name. The instrument company has plants at Elmhurst, N. Y., and Glendale, Calif.

Trade Literature

Electric Tools.—Catalog, 64 pp. Describes a comprehensive line of portable electric tools, including improved 1/4- and 1/2-inch drills. The Black & Decker Mfg. Co., Towson, Md.

Carbon Brushes.—Catalog 50. Describes physical and electrical characteristics of various carbon brush grades, service requirements and selection of proper types. Becker Brothers Carbon Co., Cicero, Ill.

Speed Indicator.—Bulletin 740. Describes the Velox speed indicator, a chronometric hand tachometer, for measuring revolutions per minute up to 100,000. Herman H. Sticht & Co., 27 Park Pl., New York.

Monel Metal.—Bulletin T-9, 16 pp. Describes the engineering properties of "K" Monel, a corrosion resistant wrought alloy of nickel, copper and aluminum. The International Nickel Co., Inc., 67 Wall St., New York.

Voltage Regulators.—Bulletin GEA-2018D, 16 pp. Describes induction voltage regulators for indoor and outdoor services; 12 and 24 kva, 2,400 and 4,800 volts; for floor, platform, and crossarm mounting. General Electric Co., Schenectady, N. Y.

Running Time Meters.—Bulletin F-1. Describes synchronous motor driven running time meters for use in connection with radio transmitters, x-ray tubes, welding machines, testing laboratory equipment, etc. R. W. Cramer Co., Centerbrook, Conn.

Voltage Regulators.—Bulletin GB-234, 8 pp. Describes automatic generator voltage regulators for controlling the voltage of medium-size single or polyphase a-c generators excited by individual exciters. Burlington Instrument Corp. Burlington, Ia.

Low Voltage Cables.—Bulletin GEA 3280, 20 pp. Described as a condensed guide to aid in the selection of insulated cable for low-voltage power circuits. Types treated include varnished-cambric insulated; Glyptal insulated leads; Versatol insulated cable; Flamenol, a new synthetic wire; type RR-tellurium parkway cable and tellurium-jacketed portable cable. General Electric Co., Schenectady, N. Y.

Flexible Couplings.—Catalog 443, 44 pp. Explains the functions of flexible couplings and illustrates how "Gearflex" couplings compensate for parallel or angular misalignment. Includes applications, ratings, dimensions and weights of various available types and proper method of selection for any desired application. Farrel-Birmingham Co., Inc., 344 Vulcan St., Buffalo, N. Y.

Remote Liquid Level Gauge.—Bulletin G-12, 8 pp. Describes a new, remote reading, liquid level gauge applicable wherever large quantities of oil or other liquids are stored in tanks, and capable of measuring liquid levels in tanks of every type to the nearest one-eighth inch. An indicator panel can be connected to any number of tanks. Guardian Electric, 1621 W. Walnut St., Chicago, Ill.

Electroplating Rack Tape.—Bulletin WR-101. Describes an improved covering for electroplating racks, consisting of a synthetic, thermoplastic resin in tape form, resistant to all cleaning, pickling and plating solutions commonly used. Hanson-Van Winkle-Munning Co., Matawan, N. J.

Metal-clad Switchgear.—Catalog AE 8-b, 12 pp. Describes a new line of moderate duty, vertical lift, metal-clad switchgear for control of generators and distribution facilities of central stations, industrial plants, office buildings, etc. with services of 5,000 volts or less, at interrupting capacities of 25,000 and 50,000 kva. Includes dimensional data, circuit arrangements and full specifications for indoor services. Roller-Smith Co., Bethlehem, Pa.

Mercury Arc Rectifiers.—Bulletin B6064, 40 pp. Describes standard multi-anode rectifiers and the recently announced Excitron single-anode rectifiers, particularly suited for the lower voltage applications from 250 to 300 volts. In addition to outlining the numerous advantages of this type of conversion equipment, it includes many shop and installation views. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

Capacitor-Motor Servicing Equipment.—Catalog 168A, 8 pp. Describes a new "Test-Mike" and "Service-Mike" for a-c, motor starting capacitor service tests. Details are included on the locked-rotor torque test, methods of making tests, selection of capacity value, making permanent repairs, check on overloads, with additional service notes; and connection diagrams and a diagram of switch positions. Cornell-Dubilier Electric Corp., S. Plainfield, N. J.

Motors and Lighting Circuit Equipment.—Cat. 30-000, 60 pp., termed the "Quick Selector" catalog and designed to help the user of electrical apparatus in selecting the right equipment for a motor or lighting circuit. Safety switches, "Nofuze" circuit breakers and multibreakers with ratings of from 25 to 600 amperes on alternating voltages up to 600, various types of panelboards, motor control devices, and motors are featured; general application data includes NEC recommended installation practices, simplified and tabulated for easy reference, and circuit diagrams and tables. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

100 Times More Light!

NEW POSSIBILITIES in the application of stroboscopes to the study of motion are opened with the new Type 648-A STROBOLUX . . . the auxiliary unit which furnishes over 100 times as much light as the popular STROBOTAC.

With the STROBOLUX it is no longer necessary to shield the machine or part under observation from extraneous light in order to s-t-o-p motion. The STROBOLUX, when used under proper conditions, supplies sufficient illumination for single-flash still pictures. High speed movies (up to 100 frames per second) are now possible with this simple auxiliary light source.

The STROBOLUX is a completely self-contained accessory which is fired by and must be used with the STROBOTAC. Appropriate cords for connecting the two units are supplied. An outlet is built into the STROBOTAC so that single flashes for photographic study can be tripped electromechanically, by means of a photo cell, or with a microphone and amplifier.

The STROBOLUX is priced at $175.00. If you now own a STROBOTAC it will be equipped with appropriate outlets to operate the STROBOLUX, without charge, when ordering the STROBOLUX.

The STROBOLUX adds immeasurably to the utility of G-R stroboscopic equipment in engineering, design, production, maintenance and sales. Let us show you how!

● *Write for Bulletin 533*

GENERAL RADIO COMPANY

CAMBRIDGE, MASSACHUSETTS

Branches in New York and Los Angeles

New Products

Assembly Multiplies Magnet Strength.—A new permanent magnet assembly, roughly three times as strong as any previously known, is a recent development of the

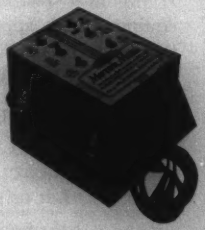
General Electric research laboratory. It permits a tiny piece of sintered alnico to lift and hold 4,450 times its own weight. Sintered alnico is an alloy of aluminum, nickel and iron as the basic or essential ingredients, and is made by pressing together the powdered metals and heating almost to the melting point. By itself, without the special assembly, an alnico magnet has a normal lifting power of 500 times its own weight. A new mounting of brass and iron in which the magnetic flux passes through many air gaps, instead of the usual two, in bridging from pole to pole, is responsible for the greatly increased power. The new assembly is not a commercial development and the largest turned out in the laboratory to date contains but three cubic centimeters of alnico. Though smaller than a thimble, and weighing three-fourths of an ounce, this magnet in its mounting has supported as much as 200 pounds in tests.

Phase Monitor.—This dual phase monitor, (type 798) developed by Victor J. Andrew, 6429 S. Lavergne Ave., Chicago, Ill., while embodying the electrical principles of an earlier type, has been designed for standard mounting. The instrument actually consists of two complete phase monitors mounted as a single unit, allowing simultaneous monitoring of two phase angles. Each angle is indicated directly in degrees on a large d-c panel instrument. Meters are ordinarily calibrated between 0 and 180 degrees, though they may be used for third and fourth quadrant work. While the instrument has been designed as an aid to adjustment and maintenance of the phasing networks of a three-element, directional radio transmitting antenna, it is applicable wherever a rugged, low energy consumption, vacuum tube voltmeter type, direct reading phase monitor is required.

Voltage Regulator.—The new, type V-11, rocking contact voltage regulator for control of small a-c and d-c generators, introduced by the Allis-Chalmers Manufacturing Company, Milwaukee, Wis., is more sensitive, quicker acting, and of greater capacity than the company's earlier small regulator models. There are no vibrating contacts, tubes, or other parts requiring replacement or readjustment at frequent intervals. Only two simple adjustments are necessary at the time of installation, since all major adjustments are made at the factory. The regulator consists of a sensitive solenoid-actuated plunger which acts upon a main shaft, rocking a special contact sector over

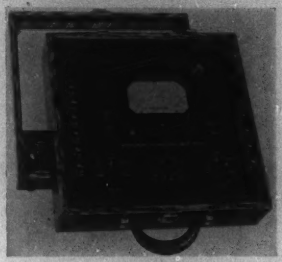
the inner surface of a commutator, the segments of which are permanently connected to the regulating resistance.

Capacitor Indicator.—In addition to incorporating many unique features as a motor starting capacitor indicator, "Motormike", developed by the Sprague Products Company, North Adams, Mass., serves as an



emergency condenser for 110-volt, 60-cycle motors where capacities from 54 to 180 mfd are required. The device indicates promptly and accurately what capacity should be used as a replacement on refrigerators, etc., and if the proper replacement is not immediately available, it can be left in the circuit as long as necessary. The "Motormike" is enclosed in a steel case, $7^1/_8$ by $6^1/_2$ by 6 inches, equipped with a carrying handle, and will safely withstand substantial overloads.

Circuit Tester.—Possessing wide flexibility of use for individual measurements on all types of control and signal equipment and electronic apparatus, this new instrument (model 785) of the Weston Electrical In-



strument Corporation, 664 Frelinghuysen Ave., Newark, N. J., has 27 complete ranges for voltage, current and resistance measurements. Among its applications are the checking of sensitive relays, signal systems, cathode ray tubes, remote control circuits, public address systems; measuring photocell currents, telephone circuits, a-c and d-c commercial motor voltages, etc. The sensitivity of the instrument permits voltage, current, and resistance measurements on oscilloscope circuits. The device employs a standard unicell on all ranges where any appreciable current is drawn by the ohmmeter circuit. In addition, two 7.5-volt batteries are used to supply energy for the high resistance ranges only. The instrument accuracy on d-c voltage and current measurements is within 2 per cent (excluding the 1,000-volt range, which has an accuracy within three per cent). Because of the new temperature-compensated rectifier circuit employed, a high accuracy on a-c voltage of within 3 per cent is permitted. Dimensions of the case are 13 by $12^1/_2$ by $5^1/_2$ inches. The complete weight of the device in the oak carrying case, including batteries, is only $13^1/_8$ pounds.

Lift Truck for Cable Reels.—A lift truck that makes it possible for one man to handle emptied or loaded cable reels, with speed and safety, has been introduced by the Barrett-Cravens Company, 3255 W. 30th St., Chicago, Ill. Cable can be readily paid out while the reel is suspended on the

trunnions of the truck and the handling of reels in warehouses, factories, and on installation jobs is greatly facilitated. The design permits reels of any diameter to be handled.

REA to Promote Sale of Appliances

Far-Sighted Selling

THESE HEADLINES STRESS THE IMPORTANCE OF ADEQUATE LINE CAPACITY

Refrigerator ... Up 53% for 6 Months

Show Light Lost by Undersized Wire

Lighting Market Can Be Quadrupled

Primary Load Up 9.1%

Washer Shipments Rise

Iowa Utility Extends Load Building Dri...

Refrigerator Sales Continue Advance

Line Building Program Anticipates Added Load

Appliance Sales Soar in Mississippi Drive

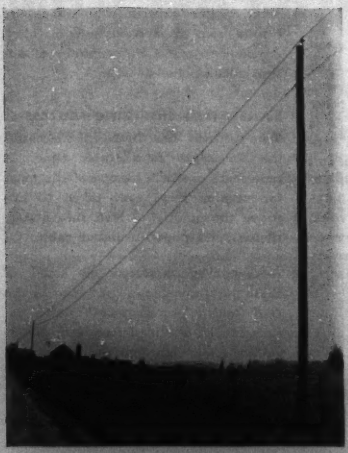
Appliance Sales Continue Upward Trend

Intensive Load Building Now Major Rural Job

Kellogg says industry is faced with making investments in rural lines successful and electricity useful to millions more citizens —

Rural Sales Meeting to Be Held by E.E.I.

Vacuum Cleaner Sales Up



After a rural line is promoted, planned and built, demands for power must be built up. There can be no happy ending to this story unless the line becomes a paying proposition.

Can there be a happy ending to the story of your lines? By insisting on A.C.S.R. conductors, you can make certain that they'll have sufficient current carrying capacity to become self-supporting.

A.C.S.R. provides the highly desirable combination of high strength, resistance to corrosion and high conductivity which makes possible the construction of high quality, low cost lines. A.C.S.R. has a long history, over a quarter of a century, of successful performance.

ALUMINUM COMPANY OF AMERICA, 2149 Gulf Building, Pittsburgh, Pennsylvania.

A·C·S·R

Aluminum Cable Steel Reinforced

FOR SUPERIOR STRENGTH AND POWER TRANSMISSION

QUESTION:

Can You Name

5 IMPORTANT

WIRE AND CABLE DEVELOPMENTS MADE IN 1939?

★ ★ ★

ANSWER:

1. **FORMEX** Magnet Wire
2. **THINWOL** Control Cable
3. **NO. 1799 Varnished-cambric Cable**
4. **GAS-FILLED Paper-Insulated Cable**
5. **NEW LEAD-SHEATHING PROCESS**

CREDIT 1939 with being an outstanding year for insulated cable. More important G-E cable developments were brought to successful conclusion than in any other year that we can recall. These developments deserve attention for the savings, improved safety, and other far-reaching benefits that they make possible.

1. FORMEX

FORMEX identifies a new G-E magnet wire that consists of a copper conductor coated with a high-quality insulating film of synthetic resin. In addition to excellent electrical characteristics, Formex magnet wire has outstanding mechanical properties. It is remarkably strong, tough, and flexible, and needs no additional protective covering. It can be wound at very high speeds, and utilizes coil space to the maximum advantage. Thus, it offers many opportunities for making improvements in the design of electric equipment.

2. THINWOL

THINWOL is a new 85-per-cent new-rubber insulated cable for fire-alarm, traffic-signal, supervisory, and other multiconductor control circuits. This new insulation has a guaranteed tensile strength of 3500 lb per sq in.; average test results show 5250 lb per sq in. An insulation thickness of 0.015 inch will stand a test of 1500 volts. Therefore, the cable can be made with very thin walls—thus saving space—and still have an increased factor of safety.

3. NO. 1799 CAMBRIC

This is a new varnished-cambric cable that has extra heat resistance. The cable can be run at a conductor temperature of approximately 10 deg C higher than the former G-E design. Of course, this means savings in copper, in overall diameter, in weight, in duct space, and in first cost.

4. GAS-FILLED CABLE

This development was announced in a paper presented at the A.I.E.E. winter meeting in New York on January 26, 1939. Gas-filled cable offers many advantages over other types of cable in the voltage range from about 15,000 to 33,000 volts. While this development is still considered somewhat in the experimental stage, the results from the systems now installed continue to prove the accuracy of design calculations.

5. NEW LEAD-SHEATHING PROCESS

This process has been in successful use for some considerable time. It represents, we believe, one of the most far-reaching steps ever taken to improve the quality of lead sheath particularly on paper-insulated cable.

Additional information on some of these developments is contained in the *G-E Review*, January, 1940. Other details can be obtained from one of our cable specialists through the nearest G-E sales office. General Electric Company, Schenectady, New York.

GENERAL ELECTRIC

660-130

IMPROVED PERFORMANCE

WITH NATIONAL CARBON BRUSHES

TRADE-MARK

● Performance of electrical equipment in transportation service is influenced to a marked degree by the proper selection and application of one small item—CARBON BRUSHES. Many transportation systems have improved performance by adopting "National" Carbon Brushes.

The engineering staff of National Carbon Company, Inc. is prepared to accurately analyze the factors involved in every brush application and to select, from an excellent assortment of brush materials, the grades capable of giving best performance on your equipment.

USE "NATIONAL" CARBON BRUSHES FOR DEPENDABLE AND SATISFACTORY PERFORMANCE

When insulated shunt cables are required, glass fabric sleeving will be supplied if specified.

NATIONAL CARBON COMPANY, INC.

Unit of Union Carbide and Carbon Corporation ■ Carbon Sales Division, Cleveland, Ohio

Connectors for tube, cable, bar, rod

Words of praise have been pouring in from all sections of the country from engineers who have received a copy of the 325 page Burndy Catalog 40. This "Handbook of Electrical Connectors" is the answer to YOUR connection need, whether your problem be simply the connection of No. 6 wires or an involved power connection of specially shaped tubing to flat bar. A note on your company letterhead will bring this valuable reference catalog to your desk. Delivery will be made by our representative in your territory. Address requests to Burndy Engineering Company, 459 East 133 Street, New York City, N. Y.

BURNDY
ENGINEERING CO., INC.

For capacities above 200 VA. Housing type.

From 20–200 VA. Primary cord set, and output receptacle.

A new unit for applications up to 15 VA. Equipped with leads or terminals.

Whether it's 1 VA for an instrument or 10 KVA for a production line—if your needs call for stable voltage at all times, SOLA CONSTANT VOLTAGE TRANSFORMERS will deliver for you.

Fully automatic, instantaneous in operation. SOLA CONSTANT VOLTAGE TRANSFORMERS have no moving parts and require no maintenance. They are self-protecting and cannot be damaged by short circuit. AND—they will maintain their output voltage to within a fraction of a percent of the specified value, even though the line voltage varies **as much as thirty percent.**

You can build a SOLA CONSTANT VOLTAGE TRANSFORMER into your product and stop worrying about your customer's line voltage.

You can build a SOLA CONSTANT VOLTAGE TRANSFORMER into your production line or your laboratory and know that every test will be made under the same line conditions.

You'll find these SOLA CONSTANT VOLTAGE TRANSFORMERS surprisingly compact—and economical, too. To augment or replace non-regulating types, standard designs are available, or units can be built to your special specification.

Write for catalog **ACV-22**

SOLA

SOLA ELECTRIC CO. 2525 Clybourn Chicago, Illinois

•

Use the STATISCOPE

FOR A.C.

and KNOW that circuits are alive or dead

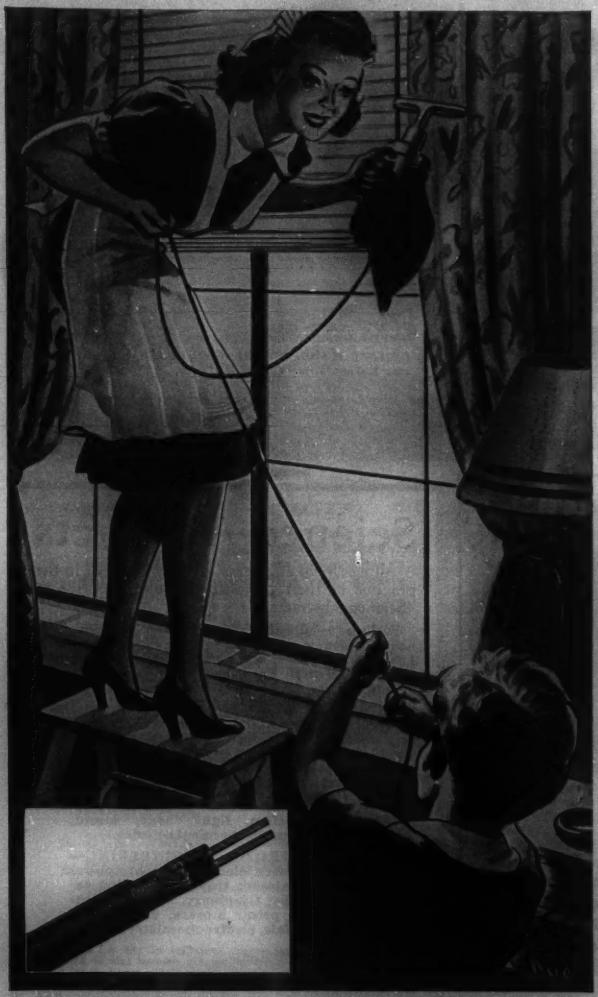
•

Write for Circular

•

MINERALLAC ELECTRIC COMPANY
25 N. Peoria St., Chicago, Ill.
50 Church St., New York City

From Portable Cords to



RUBBER INSULATED POWER CABLES

OVER 60 TYPES OF ROEBLING ELECTRICAL WIRES AND CABLES

Bare Wire and Strand—pigtail, braided copper, trolley

Magnet Wire

Rubber Insulated Wires and Cables:
Building Wires
Service Entrance Cable
Power Cables
Portable Power Cables
Parkway Cables, metallic and non-metallic
Appliance Cords
Fixture Wire

Varnished Cambric Wires and Cables

Paper Insulated Cables

Telephone Wires and Cables

And a wide variety of other wires and cables, either Standard or to Customer's Specifications

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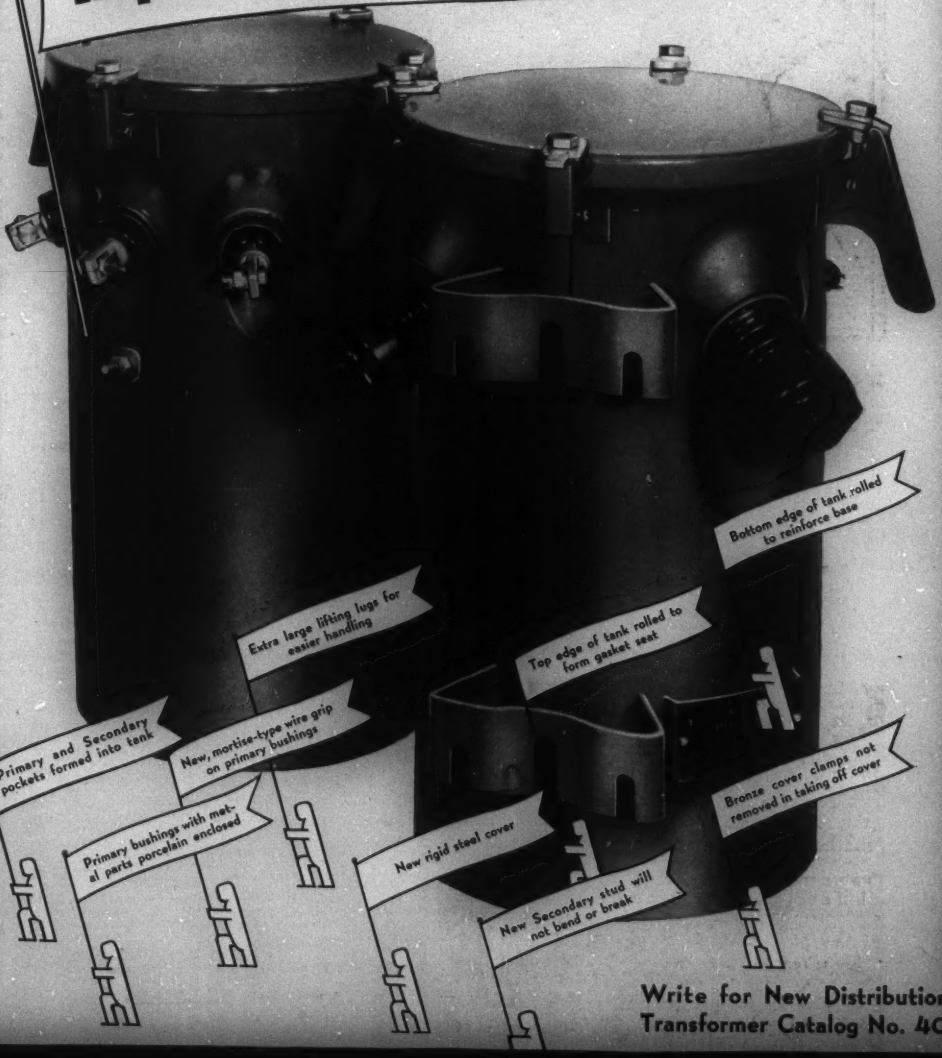
ANNOUNCING

A new pocket-type round tank transformer improved in 9 ways by Kuhlman

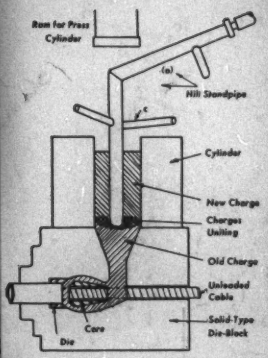

Primary and Secondary pockets formed into tank
New, mortise-type wire grip on primary bushings
Extra large lifting lugs for easier handling
Top edge of tank rolled to form gasket seat
Bottom edge of tank rolled to reinforce base
Primary bushings with metal parts porcelain enclosed
New rigid steel cover
New Secondary stud will not bend or break
Bronze cover clamps not removed in taking off cover

Write for New Distribution Transformer Catalog No. 40

KUHLMAN ☆ ELECTRIC COMPANY

DAY CITY MICHIGAN

7 Important Improvements in LEAD SHEATHING



The Hill Standpipe method of filling lead cylinder to obtain complete bonding of old and new charges; (a) the Standpipe in operating position; (c) control handles by which stream of new lead is directed against all portions of old charge. Our booklet, "Cable Sheathing with Stabilized Lead" gives full particulars of these new and better lead sheaths.

Lead sheaths for Okonite-Callender paper cables are made by means of a new technique (the Hill Standpipe illustrated above) from lead refined by a new process.

This "stabilized" lead refining process provides lead press charges which are purer to begin with and which, to a marked degree, resist oxidation during the sheathing operation. As a result of the combination of the two methods, the lead sheaths we provide today,

1. **Have no flow lines.**
2. **Contain no "critical" region.**
3. **Are free from laminations.**
4. **Assure better bonding of crystals.**
5. **Will stand high pressures.**
6. **Will give improved service records.**
7. **Are uniform from end to end and around their entire circumference.**

THE OKONITE-CALLENDER CABLE CO., INC.

PATERSON, NEW JERSEY

New York Boston Chicago Dallas

AN AFFILIATE OF THE OKONITE CO.

Seattle Buffalo Executive Office: Passaic, New Jersey Detroit Atlanta

Philadelphia Los Angeles Pittsburgh Cleveland St. Louis Washington San Francisco